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ENERGY
COMMISSION

PRELIMINARY CHARACTERIZATION OF WEST COAST STATES FOR GEOLOGIC CARBON SEQUESTRATION

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

Preliminary Characterization of West Coast States for Geologic Carbon Sequestration is a final report for the West Coast Regional Carbon Sequestration Partnership project (contract number 500-02-

004, work authorization number MR-021) conducted by various public and private organizations and managed by the California Institute for Energy and Environment.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

Phase I of the West Coast Regional Carbon Sequestration Partnership (WESTCARB) project characterizes geological sinks for carbon dioxide (CO_2) sequestration in California, Nevada, Oregon, and Washington. Results indicate geologic storage opportunities in saline formations, oil and gas reservoirs, and coal beds. Focusing on sedimentary basins as the initial most-promising targets for geologic sequestration, the project developed geographic information system (GIS) layers showing sedimentary basins and the oil, gas, and coal fields in those basins. GIS layers were attributed with subsurface information (where available), including sediment thickness, presence and depth of porous and permeable sandstones, and reservoir properties.

California offers outstanding sequestration opportunities because of its large CO_2 storage capacity and the potential of value-added benefits from enhanced oil recovery (EOR) and enhanced gas recovery (EGR). Estimated storage capacity of saline formations in California's ten largest basins ranges from 75 to 300 gigatonnes (Gt) of CO_2. Potential CO_2-EOR storage is estimated at 3.4 Gt. Cumulative production from gas reservoirs suggests a CO_2 storage capacity of 1.7 Gt.

In Oregon and Washington, coastal sedimentary basins also offer sequestration opportunities—notably in Puget Trough Basin, which contains deep coal formations that may have potential for enhanced coal bed methane recovery as well as for sequestration.

Keywords: Carbon sequestration, geologic sequestration, sedimentary basins, saline formations, enhanced oil recovery, EOR, enhanced gas recovery, EGR, enhanced coal bed methane, ECBM, West Coast Regional Carbon Sequestration Partnership, WESTCARB

Executive Summary

Introduction

Carbon capture and sequestration technologies could play a critical role in reducing the impact of fossil fuel–based power generation on the buildup of the greenhouse gas carbon dioxide (CO_2) and resulting climate change. As such, the West Coast Regional Carbon Sequestration Partnership (WESTCARB), under the direction of California Energy Commission's Public Interest Energy Research Program, is conducting research to define least-cost greenhouse gas mitigation strategies appropriate for California and the western United States and Canada, including an assessment of the potential for sequestration of CO_2 in deep geologic formations.

Purpose of Project

This report summarizes the characterization of regional geological "sinks" (potential storage reservoirs) carried out as part of Phase I (2003–2005) of the WESTCARB project. The report reviews 104 sedimentary basins in California, assesses oil and gas reservoirs in California, and provides an initial characterization of sedimentary basins and deep coal seams for sequestration in Washington and Oregon, as wells as a preliminary assessment of sedimentary basins in Nevada.

Project Approach

Work focused on sedimentary basins as the initial most promising targets for geologic sequestration. The approach for characterizing geological sinks in the different states followed similar steps:

1. The extent (area) of the sedimentary basins was determined and entered into a geographic information system (GIS) layer.
2. Baseline data were collected and preliminary screening conducted—using such criteria as the presence of porous sediments, depth, and restricted access—resulting in a list of basins for which more detailed data on geologic properties were obtained. Priority was given to basins offering potential for value-added benefits from enhanced oil recovery (EOR), enhanced gas recovery (EGR), or enhanced coal bed methane (ECBM) recovery. Data from reservoirs in these basins form the bulk of the characterization data.
3. CO_2 storage capacity was evaluated where sufficient data were available. Ultimately, the characterization data were integrated with source and transportation data to evaluate economics and develop supply curves for regional source/sink options; these results are presented in a companion WESTCARB report by Herzog et al. (2007).

In California, the screening process excluded basins from further consideration on the basis of insufficient depth (<800 m, or <2,625 ft), lack of porous or permeable rocks, or lack of identifiable seals. Basins underlying national parks and military installations were also excluded from further consideration. Of the 104 basins evaluated to date, 77 have been excluded for one of the reasons listed above. In conjunction with this effort, the California Geological

Survey (CGS) prepared depth-to-basement and sandstone isopach maps of major sedimentary basins for which geophysical or well log data were available.

The oil and gas reservoirs in California were assessed by compiling and analyzing published state data, including discovery date and well, deepest well and depth, well locations, field area, cumulative production, base of freshwater, and specific physical rock and fluid properties for each producing, idle, or abandoned zone within each field. Results are being used to screen fields for CO_2 storage potential and to identify depleted or abandoned fields for CO_2-EOR or sequestration opportunities.

In Nevada, the minimum basin depth criterion was taken as 1,000 meters (3,300 feet) due to a generally higher geothermal gradient in the Basin and Range province. An approach to account for the proximity of potential sinks to faults and mineral and geothermal resources was developed, and a conceptual model for saline formations and oil and gas reservoirs was created.

In Oregon and Washington, information on coal formations as potential sinks was compiled, as were data on the overall geology of sedimentary basins. For coal, available data on coal rank, percentage of methane saturation, and sorbtive capacity were compiled, in addition to other reservoir properties.

Conclusions

Phase I work to date shows that excellent geologic storage opportunities exist in the WESTCARB region within each of the major types of geologic sinks: saline formations, oil and gas reservoirs, and coal beds.

California offers outstanding opportunities because of its large capacity and the potential of value-added benefits from EOR and EGR. Estimated storage capacity of saline formations in the 10 largest basins in California ranges from about 75 to about 300 gigatonnes (Gt) of CO_2, depending on assumptions about the fraction of the formations used and the fraction of the pore volume filled with separate-phase CO_2. The low end of this range would provide sufficient capacity for storing about 500 years of utility and industrial-sector emissions at current emission rates.

The first sequestration targets are likely to be oil reservoirs where CO_2-EOR can help offset overall capture and storage costs. In California, most oil reservoirs are found in the San Joaquin Basin, Los Angeles Basin, and southern coastal basins. WESTCARB investigators estimate a potential CO_2-EOR storage of 3.4 Gt, based on a screening of reservoirs using depth, an API gravity cutoff, and cumulative oil produced. Capacity estimates will be further refined in Phase II (2005–2009).

There are abundant gas reservoirs in the Sacramento Basin, including Rio Vista, the largest onshore gas field in California, which has produced over 9.3×10^{10} m^3 (3.3 Tcf) of natural gas since 1936. The cumulative production from gas reservoirs (screened by depth) in this basin suggests a CO_2 storage capacity of 1.7 Gt.

In Oregon and Washington, sedimentary basins along the coast offer sequestration opportunities. Of particular interest is the Puget Trough Basin, which contains up to 1,130 m (3,700 ft) of unconsolidated sediments overlying up to 3,050 m (10,000 ft) of Tertiary sedimentary rocks. The Puget Trough Basin also contains deep coal formations, which are sequestration targets and may have potential for ECBM. The amount of unmineable coal in the Puget Sound basin was estimated to be over 70 billion tons, with a CO_2 storage potential of 2.8 Gt.

In Nevada, many small basins were identified, but there is generally a paucity of information on the structure and properties of these sediments. The potential for mineral storage techniques using mafic rock and for EOR in Nevada will be assessed in Phase II.

Benefits to California

This research benefits the State of California and California's electricity ratepayers by identifying areas where carbon dioxide could be sequestered deep underground in geologic formations. Geologic carbon sequestration is a greenhouse gas reduction technology with high potential, but its application in California and the western United States has been little studied thus far.

1.0 Introduction

One proposed method for decreasing atmospheric concentrations of carbon dioxide (CO_2), a key greenhouse gas associated with global climate change, is to capture the CO_2 at large stationary sources and sequester it underground in deep geologic sinks. This is called carbon capture and sequestration (CCS). Underground injection of CO_2 could not only mitigate global warming, but may also prove useful in extracting fossil fuels through such methods as enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coal bed methane recovery (ECBM)

The West Coast Regional Carbon Sequestration Partnership is one of seven regional partnerships established by the U.S. Department of Energy (DOE) to evaluate CCS technologies best suited for different regions of the country. The West Coast Region includes the states of California, Alaska, Arizona, Nevada, Oregon, Washington, and the Canadian province British Columbia. Led and co-funded by the California Energy Commission, WESTCARB is a consortium of more than 80 organizations, including state natural resource and environmental protection agencies, national laboratories and universities, private companies, utilities, oil and gas companies, and nonprofit organizations. As part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB) Phase I effort, several partner organizations developed preliminary baseline information concerning geologic options for CO_2 sequestration in the western United States—specifically, California, Nevada, Oregon, and Washington.

As a first step, the potential sequestration capacity of appropriate geologic sinks—with and without fossil fuel recovery opportunities—needed to estimated. To this end, WESTCARB has undertaken the characterization of geological sinks throughout its region.

This report summarizes Phase I results for this WESTCARB project. Work focused on sedimentary basins—and the oil and gas fields found within them—as the initial most-promising targets for geologic sequestration. This report reviews 104 sedimentary basins in California, assesses oil and gas reservoirs in California, and provides an initial characterization of sedimentary basins and deep coal seams for sequestration in Washington and Oregon, as wells as a preliminary assessment of sedimentary basins in Nevada.

2.0 Methods

2.1. Characterization Methodology

WESTCARB has focused on sedimentary basins as the initial most-promising targets for geologic sequestration. The partnership's approach for various states has followed similar steps. First, the extent (area) of the basins is determined and entered into a geographic information system (GIS) layer. Second, baseline data are collected and preliminary screening is conducted using such criteria as the presence of porous sediments, depth, and restricted access, resulting in a list of basins for which more detailed data on geologic properties are to be obtained. Priority is given to basins in which there are potential value-added benefits from enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coal bed methane recovery (ECBM). Data from reservoirs in these basins form the bulk of the characterization data. The third step entails evaluating CO_2 storage capacity. The final step integrates the characterization data with source and transportation data to evaluate economics and develop supply curves for regional source/sink options.

2.1.1. California

In California, the California Geologic Survey identified and catalogued sedimentary basins within California's 11 geomorphic provinces (Downey and Clinkenbeard 2006). Selected basins included all large or hydrocarbon-producing basins, as well as numerous smaller basins identified from the 1:750,000 scale geologic map of California (Jennings et al. 1977). Where basins extended offshore, only the onshore portions were considered. This resulted in an inventory of 104 basins, outlines of which were digitized to produce a California sedimentary basin GIS layer. This layer was combined with a California oil and gas field layer to illustrate the distribution of known oil and gas fields.

Basins were screened to determine preliminary suitability for potential CO_2 sequestration, with those basins not meeting the screening criteria excluded from further consideration. Screening involved literature searches and analysis of available well logs. Criteria included the presence of significant porous and permeable strata, thick and pervasive seals, and sufficient sediment thickness to provide critical-state pressures for CO_2 injection (>800 m, or >2,625 ft). Accessibility was also considered, with basins overlain by national and state parks and monuments, wilderness areas, Bureau of Indian Affairs–administered lands, and military installations being excluded. Most of the basins excluded for this reason are located in the arid desert valleys of the Basin and Range and Mojave Desert geomorphic provinces. Structural closure or stratigraphic trapping was not considered a prerequisite for saline aquifers at the screening level.

To identify areas of adequate sedimentary fill, depth-to-basement contour maps were prepared for those basins containing sufficient basement penetrations. This included the Sacramento, San Joaquin, and Salinas basins. In some producing basins, where basement well control is limited or absent, basement contour maps were extrapolated from shallower structure maps (Eel River Basin), or published geophysical depth-to-basement maps were used (Los Angeles, Ventura basins).

To characterize potential saline aquifers and hydrocarbon reservoirs, oil and gas field and reservoir data were assembled for depleted and producing fields. Data were compiled in field-level and reservoir-level databases and attributed to the California oil and gas field GIS layer for manipulation and spatial analysis by other WESTCARB participants (e.g., Herzog et al. 2007). Field-level data included information such as location, depth, field area, cumulative production, and depth-to-base of fresh water. Field-level database parameters are shown in Table 1.

Table 1. Sample content of a Field Table database record

Field Code:	VE024
Field:	Honor Rancho Oil
Discovery Well Operator:	The Texas Co.
Discovery Well:	Honor Rancho A -1
Section:	6
Township:	4N
Range:	16W
Meridian:	SB
Discovery Date:	8/1/1950
Deepest Well Operator:	So. California Gas Co.
Deepest Well:	Wayside Unit 28
Section:	7
Township:	4N
Range:	16W
Meridian:	SB
Depth (ft):	11,747
Field Area (ac):	450
Cum. Oil Prod. (MBO):	31,098
Cum. Gas Prod. (MMCF):	52,992
Base Fresh Water:	1,150

Reservoir-specific parameters for producing, abandoned, or shut-in reservoirs in each field were compiled in the reservoir-level database. These data included reservoir fluid (oil, gas, water), zone status (producing, abandoned, shut-in), average depth, average thickness, producing area, porosity, permeability, initial pressure and temperature, formation water salinity, seal thickness, trap type (structural or stratigraphic), and history of secondary and tertiary recovery efforts. A measure of “fracture intensity” was assigned for most reservoirs to instill a general sense of fracturing and/or faulting. This subjective measure was assigned a value of low, medium, or high, based solely on the number of mapped faults illustrated in published California Department of Conservation, Division of Oil, Gas, and Geothermal Reservoirs (DOGGR) field maps (L = 0–1 fault; M = 2–3 faults; H = 4+ faults). An example of reservoir database parameters is shown in Table 2.

Table 2. Sample content of a Zone Table database record

Field Code:	VE024	Permeability (md):	20
Zone:	Modelo Fm.	Perm. Range Min. (md):	179
Age:	U. Miocene	Perm. Range Max. (md):	
Oil or Gas:	O	Pressure (lb/ft):	2,962
Date of Discovery:	12/1/1950	Press. Range Min. (lb/ft):	4,500
Zone Status (P/A/SI):	P	Press. Range Min. (lb/ft):	190
API Gravity:		Temperature (ºF):	
API Range Min.:	35	Temp. Range Min. (ºF):	
API Range Max.:	39	Temp. Range Max. (ºF):	
GOR:		Salinity (ppm NaCl):	
GOR Range Min.:	220	Sal. Range Min. (ppm NaCl):	11,200
GOR Range Max.:	1,250	Sal. Range Max. (ppm NaCl):	24,800
Sp. Gravity:		TDS (ppm):	20,200
Sp. Gravity Min.:	0.470	TDS Range Min. (ppm):	
Sp. Gravity Max.:	0.765	TDS Range Max. (ppm):	
BTU:	1,066	Seal:	Modelo Fm.
BTU Range Min.:		Seal Thickness (ft):	
BTU Range Max.:		Seal Thickness Min. (ft):	5
Cum. Oil (MBO):	29,094	Seal Thickness Max. (ft):	50
Cum. Gas (MMCF):	47,601	Trap Type:	Stratigraphic
No Pool Breakdown:		Fault Intensity:	L
Depth (ft):		ERP 1:	Gas Injection
Depth Range Min.:	6,481	ERP 1 Start:	1954
Depth Range Max.:	10,000	ERP 1 Stop:	1956
Thickness (ft):		ERP 2:	Waterflood
Thickness Range Min. (ft):	94	ERP 2 Start:	1959
Thickness Range Max. (ft):	310	ERP 2 Stop:	1966
Producing Area (ac):	400	ERP 3:	Waterflood
Porosity (%):		ERP 3 Start:	1972
Porosity Range Min. (%):	7	ERP 3 Stop:	1975
Porosity Range Max. (%):	26		

2.1.2. Oregon and Washington

In Oregon and Washington, GIS layers were developed that give the location of sedimentary basins. Data on the overall geology of sedimentary basins and the available reservoir properties were assembled (Golder Associates 2007). Data from the few available deep wells penetrating the basalt layers in the eastern portions of the states were reviewed to establish the presence of sediments at depths of 300 m (1,000 ft) to more than 2,700 m (9,000 ft). Information on coal formations as potential sinks was also compiled, including available data on coal rank, percent methane saturation, and sorbtive capacity.

2.1.3. Nevada

In Nevada, the minimum-basin-depth criterion was taken as 1,000 m (3,300 ft), owing to a generally higher geothermal gradient in the Basin and Range province. The Nevada Bureau of Mines and Geology (NBMG) developed a GIS-based screening methodology that accounts for the proximity of potential geologic sinks to faults, mineral and geothermal resources, populated areas, other restricted lands, and water resources (Price et al. 2007). The NBMG also developed a method, illustrated in Table 3 on the next page, to interrogate well records for information relevant to geologic sequestration.

Table 3. Information recorded from records of deep wells drilled in Nevada (Hess 2004)

DEFINITIONS

CO_2 reservoir rock ≡ sandstone, conglomerate, sand, or gravel

Seal rock ≡ shale, mudstone, claystone, mud, clay, halite, gypsum, salt, or nonwelded (possibly clay- or zeolite-altered) ash-flow tuff

NEITHER A CO_2 RESERVOIR ROCK NOR SEAL ≡
limestone, dolomite, fractured volcanic rock, fractured sandstone, quartzite, metamorphic rocks, or granite or other igneous rocks

Data collected from well records, if available, in wells within areas not otherwise excluded for consideration of CO_2

1. Total depth of well.
2. Are there potential CO_2 reservoir rocks in the well below 1 km (3,281 ft) depth? If no, go to next well.
3. Is there a potential seal below 1 km <u>and</u> above that reservoir rock? If no, go to next well.
4. Depth to base of Cenozoic/Tertiary volcanic rocks and alluvium.
5. Depth to base of deepest reservoir rock in pre-Tertiary sedimentary package.
6. How fresh is the water in this deepest reservoir rock? (Total dissolved solids – TDS?)
7. How porous is this deepest reservoir rock? % of porosity?
8. How permeable is this deepest reservoir rock? K in millidarcy?
9. Thickness of the thickest single pre-Tertiary reservoir rock.
10. How fresh is the water in this thickest pre-Tertiary reservoir rock?
11. How porous is this thickest pre-Tertiary reservoir rock?
12. How permeable is this thickest pre-Tertiary reservoir rock?
13. Total thickness of all pre-Tertiary reservoir rocks.
14. Thickness of the thickest single pre-Tertiary seal rock <u>above the deepest reservoir rocks.</u>
15. Total thickness of all pre-Tertiary seal rocks above the deepest reservoir rocks.
16. Depth to base of deepest reservoir rock in Tertiary sedimentary package below 1 km.
17. How fresh is the water in this deepest reservoir rock in Tertiary package?
18. How porous is this deepest reservoir rock in Tertiary package?
19. How permeable is this deepest reservoir rock in Tertiary package?
20. Thickness of the thickest single Tertiary reservoir rock below 1 km.
21. How fresh is the water in this thickest single Tertiary reservoir?
22. How porous is this thickest single Tertiary reservoir?
23. How permeable is this thickest single Tertiary reservoir?
24. Total thickness of all Tertiary reservoir rocks below 1 km.
25. Thickness of thickest single Tertiary seal rock <u>below 1 km.</u>
26. Total thickness of all Tertiary seal rocks <u>below 1 km.</u>
27. Total thickness of all Tertiary seal rocks below 1 km and above shallowest reservoir rock.
28. Thickness of halite beds below 1 km.

FACTORS THAT CAN NOW BE DERIVED FROM THESE NUMBERS

A. Total thickness of potential reservoir rocks = #13 + #24
B. Total thickness of potential seal rocks above the deepest reservoir rock and below 1 km = #15 + #26
C. Reservoir rock to seal rock ratio = #A/#B, ~ sand/shale ratio

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2.2. GIS Database Description

The GIS database for WESTCARB is housed in an Enterprise Geodatabase format using ArcSDE (Spatial Database Engine) from Environmental Systems Research Institute, Inc. (ESRI). This database can be connected directly to any ESRI ArcMap client version 9.2 or later. The data layers can also be downloaded from the Utah Automated Geographic Reference Center (AGRC; http://atlas.utah.gov/WESTCARB-GIS-data/) in a format that can be used in any common GIS software: a complete list of available geologic and associated layers is given in the Appendix. The layers are organized into the main categories of "sedimentary basins," "sources," and "base layers." The sedimentary basin category contains sub-categories of "geologic features" and "supporting data."

AGRC (with WESTCARB funding) has created an interactive web map that provides Internet access to the data layers at http://atlas.utah.gov/co2wc. In addition to providing a means by which the GIS data layers can be viewed and queried, this interactive map lets the user perform some basic analysis operations such as buffering and linear distance measurement.

In addition to compiling the WESTCARB Partnership database, AGRC continues to cooperate with the NATCARB database (www.natcarb.org) in the modeling and serving of the nationwide distributed carbon atlas. NATCARB data layers are served via ESRI's ArcIMS map services, which are harvested by the NATCARB interactive map portal. These data are also published as part of the *National Carbon Sequestration Atlas of the United States and Canada (2007)* at http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlas/Introduction.pdf.

3.0 Results and Discussion

3.1. California

3.1.1. Sedimentary Basins

Of the 27 basins which met the screening criteria, the most promising are the larger Cenozoic marine basins, including the San Joaquin, Sacramento, Los Angeles, Ventura, and Salinas basins, followed by the smaller Eel River, La Honda, Cuyama, Livermore, and Orinda marine basins. Favorable attributes of these basins include (1) geographic diversity; (2) thick sedimentary fill with multiple porous and permeable aquifers and hydrocarbon reservoirs; (3) thick, laterally persistent marine shale seals; (4) locally abundant geological, petrophysical, and fluid data from oil and gas operations; and (5) numerous abandoned or mature oil and gas fields that might be reactivated for CO_2 sequestration or benefit from CO_2 enhanced recovery operations. Results for the above basins are summarized in the following pages. More detailed discussion of these, as well as other California sedimentary basins, is found in Downey and Clinkenbeard, 2006.

The Great Valley province is an elongated topographic valley approximately 725 km (450 miles) long lying between the Sierra Nevada and the Coast Ranges, and extending from the Klamath Mountains in the north to the Transverse Ranges in the south. The Great Valley consists of a large depositional basin that has received sediments almost continuously since the Late Jurassic and contains, by some estimates, as much as 12,200 m (40,000 ft) of mostly marine, sedimentary rocks (Magoon and Valin 1995). In the subsurface, the Great Valley is divided into the Sacramento Basin in the north and the San Joaquin Basin to the south, the point of division being the buried Stockton Arch south of the city of Stockton.

The Sacramento Basin is approximately 390 km (240 miles) long and averages about 80 km (50 miles) wide. In its current form, the basin comprises an asymmetric trough with a westerly dipping basement surface ranging from surface exposures in the Sierra foothills to depths estimated to be greater than 6,700 m (22,000 ft). In contrast to the oil-prone San Joaquin Basin, the Sacramento Basin is a natural gas–producing basin.

Figure 1 is a generalized cross section from the southern portion of the basin, showing major sandstone units which constitute sequestration targets and shale units which represent regional seals. Formations containing important gas reservoirs include the Winters, Starkey, Mokelumne River, and Domengine. Porosities range from 15% to 35%, and permeabilities range from 10 to 1,700 md (DOG 1983).

A generalized sandstone isopach map of the Sacramento Basin (Figure 2) reveals good sandstone development paralleling the strike of the basin and ranging from over 300 m (1,000 ft) in Tehama County to nearly 1,220 m (4,000 ft) in Stanislaus County. The southward thickening is largely the result of the post-Cretaceous regional unconformity, which progressively truncates the sand-rich Great Valley Sequence formations to the north, leaving only Forbes and Kione formation sandstones remaining in the northernmost counties.

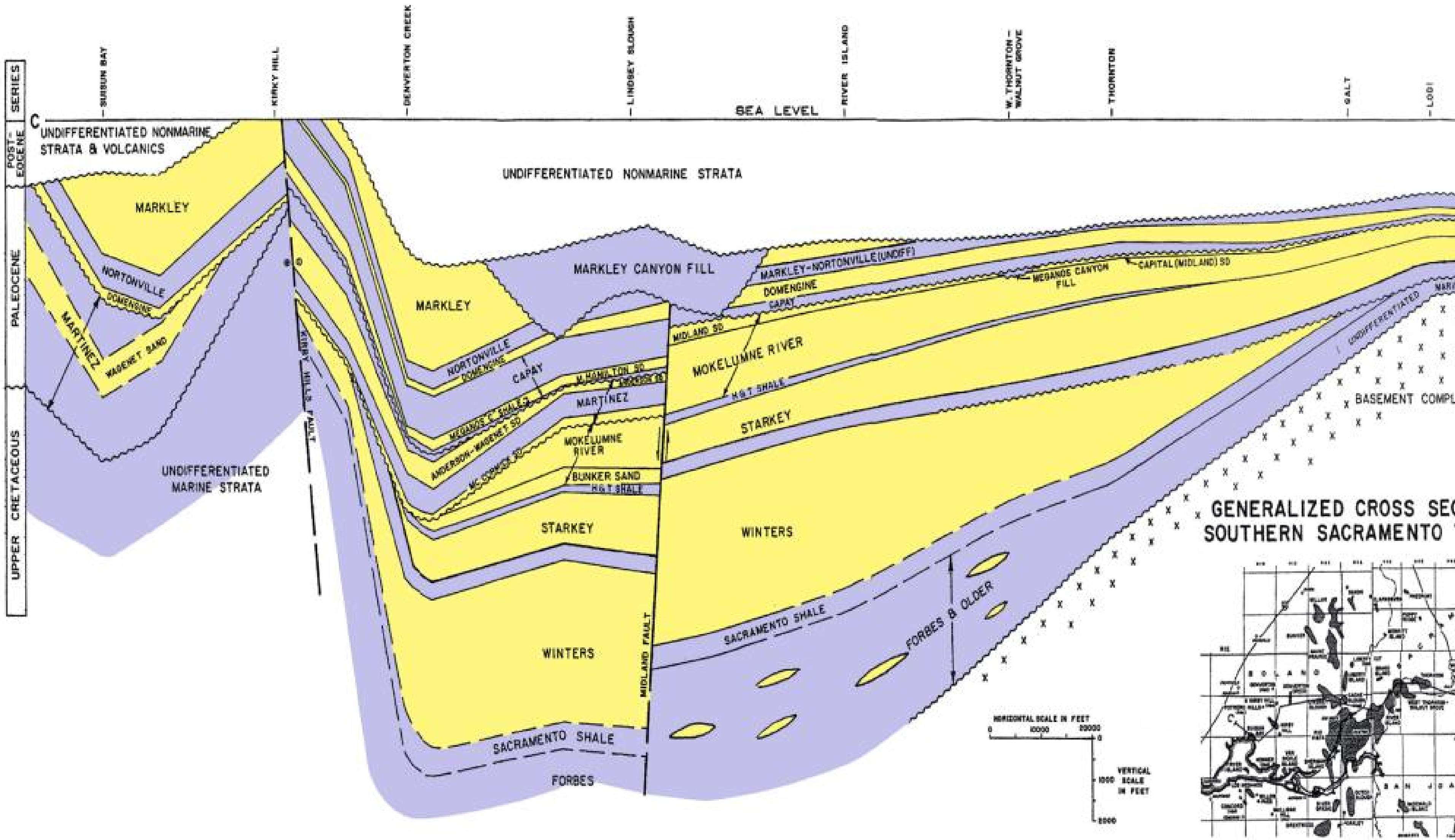

Figure 1. Generalized cross section through the southern Sacramento Valley (adapted from DOG 1983)

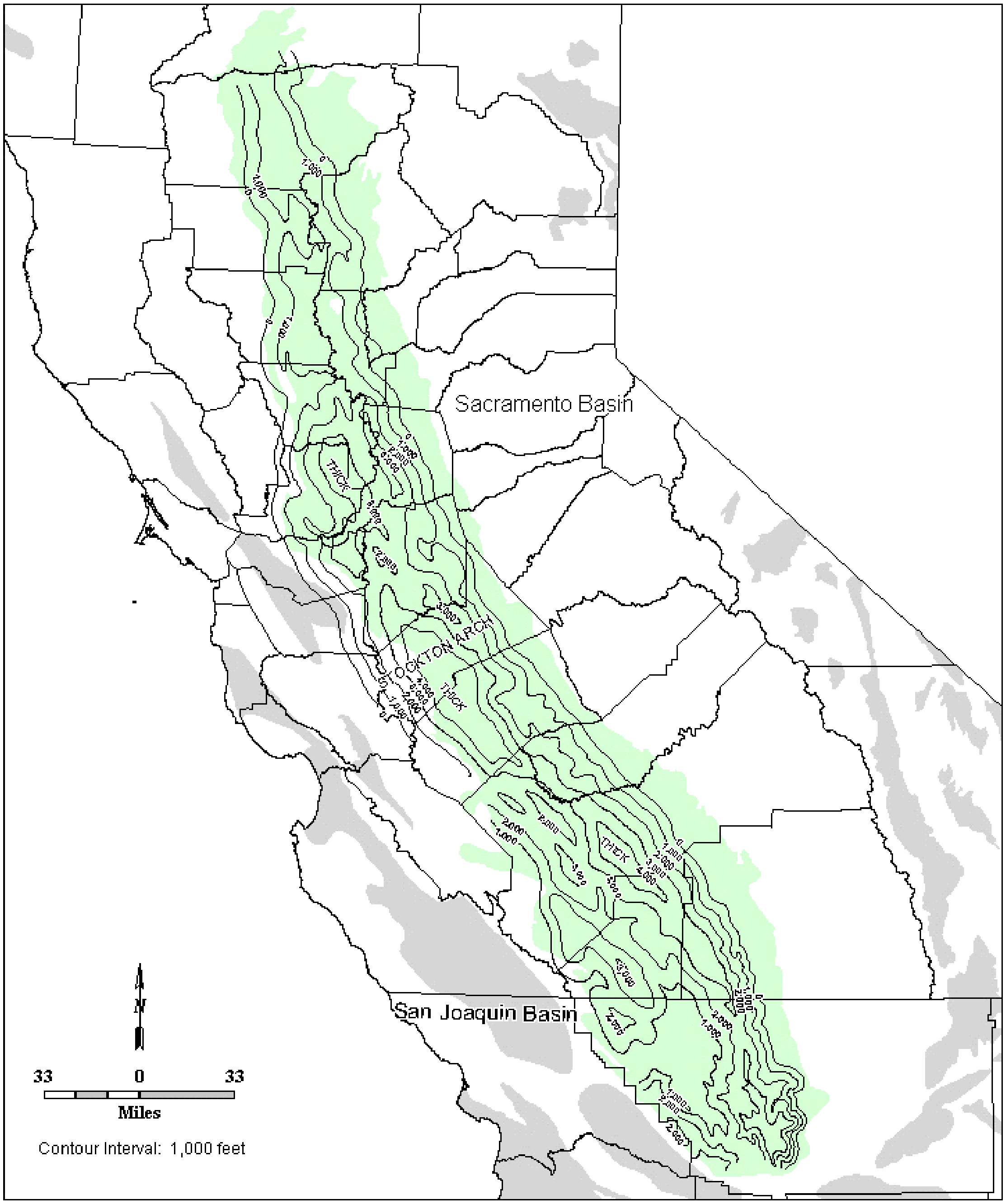

Figure 2. Generalized sandstone isopach map of the Sacramento Basin

The San Joaquin Basin comprises the southern half of the Great Valley province. It extends about 350 km (220 miles) from the Stockton Arch to its southern terminus at the northern Transverse Ranges and averages 80–115 km (50–70 miles) wide. It is bounded on the east by the Sierra Nevada and on the west by the Central Coast Ranges and the San Andreas Fault.

The basin is filled with predominantly marine Cretaceous and Cenozoic clastic sedimentary rocks that attain an aggregate thickness of over 9,150 m (30,000 ft). A generalized cross section in Figure 3 shows sandstone formations that are sequestration targets, and regional shale seals. Important oil-producing formations include the Gatchell, Vedder, Jewett, and Pyramid Hill, Temblor, Stevens, Chanac and Santa Margarita, and Etchegoin. Porosities range from 10%–40% and permeabilities from 0.2 md to 10,000 md. Porosity and permeability decrease with depth (DOGGR 1998).

A gross sandstone isopach map (Figure 2) shows that sandstone occurs in a trend thickening to over 1,220 m (4,000 ft) parallel to the basin axis. Unlike the Sacramento Basin, the isopach interval includes largely Eocene Gatchell Formation through Pliocene San Joaquin Formation sandstones deposited above the post-Cretaceous unconformity. However, some upper Cretaceous Great Valley Sequence sandstones contribute to the isopach in the northern basin, while lower beds of the Kern River and Tulare formations are included in deeper portion of the southern basin.

The Transverse Ranges are an east-west trending series of mountain ranges and valleys extending about 515 km (320 miles) from Point Arguello eastward to the Mojave Desert. The largest and most important sedimentary basin within these ranges is the Ventura Basin, a complexly folded and faulted Cenozoic marine sedimentary basin. The western two thirds of the basin extends offshore to include the Santa Barbara Channel between the Channel Islands and Santa Ynez Mountains. The onshore portion comprises about 4,079 km^2 (1,575 mi^2), including the Santa Clara Valley and Oxnard Plain. The onshore basin is bounded by the Santa Ynez and Santa Monica mountains to the north and south, respectively, and the San Gabriel Fault to the east. The Ventura Basin is the deepest of California's Cenozoic basins, containing more than 17,700 m (58,000 ft) of largely marine sediments. Consequently, the basin includes numerous upper Cretaceous through Pleistocene–age sandstones with sequestration potential, and possibly EOR opportunities. Figure 4 is a generalized cross section of Ventura Basin, which is characterized by major east-west trending thrust faults and tightly folded anticlinal trends that contain the majority of the basin's oil reserves. The Modelo and Pico sandstones are major oil-producing formations with porosities varying from 15% to 35% and permeabilities ranging from 8–6,000 md (DOGGR 1991). Porosity and permeability decrease with depth.

A sandstone isopach map for the Ventura Basin (Figure 5) reveals three thick east-west trending sandstone zones, each exceeding 1,220 m (4,000 ft) thick, as well as significant sandstone development exceeding 300 m (1,000 ft) throughout most of the basin. In the deeper parts of the basin, sandstones within the isopach interval include primarily Sespe through Pico formation sandstones. Increasing contributions of Cretaceous strata, at the expense of these Eocene through Pliocene deposits, occupy the isopach interval in the shallower basin margins.

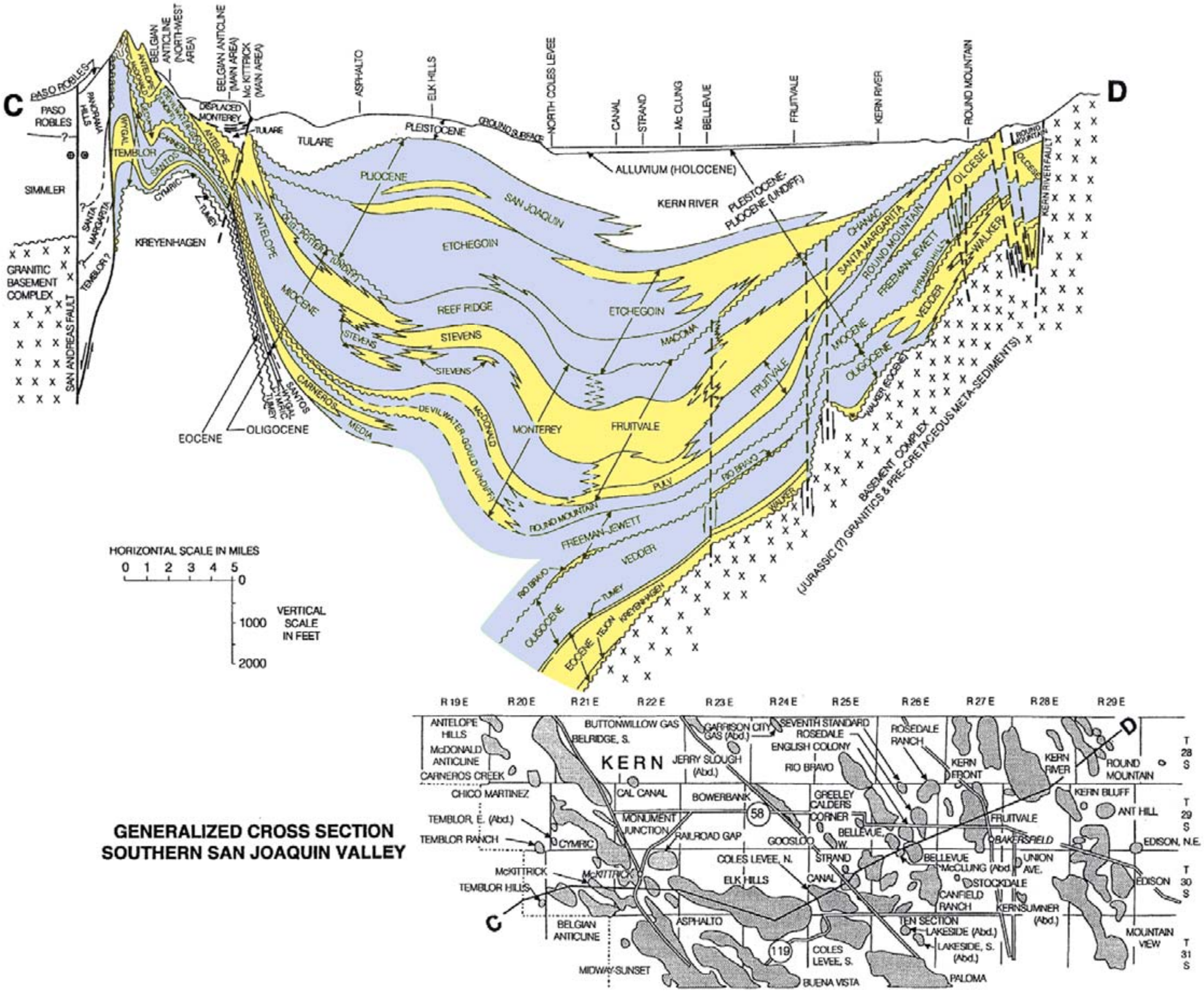

Figure 3. Generalized cross section through southern San Joaquin Valley (adapted from DOGGR 1998)

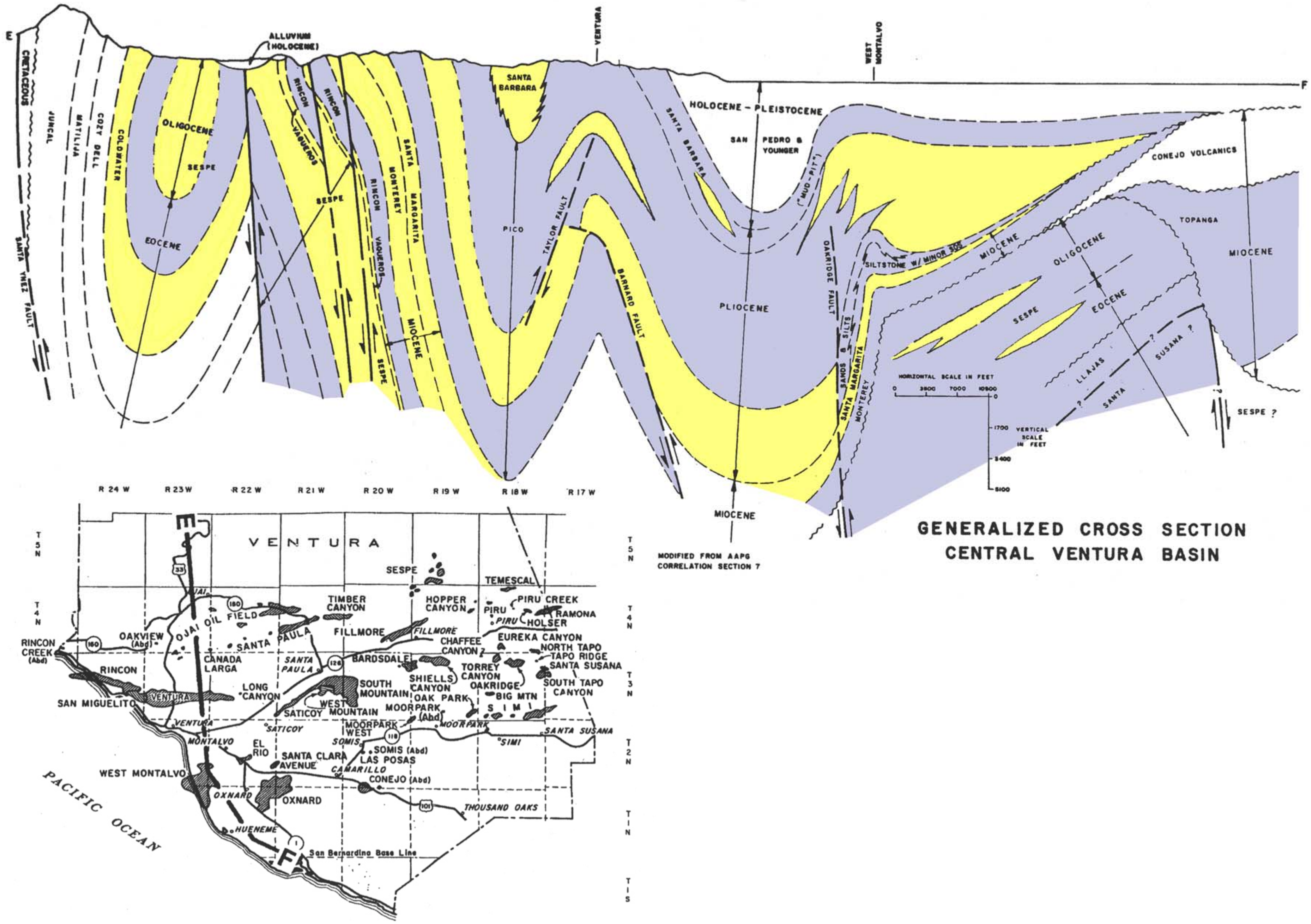

Figure 4. Generalized cross section through the Ventura Basin (adapted from DOGGR 1991)

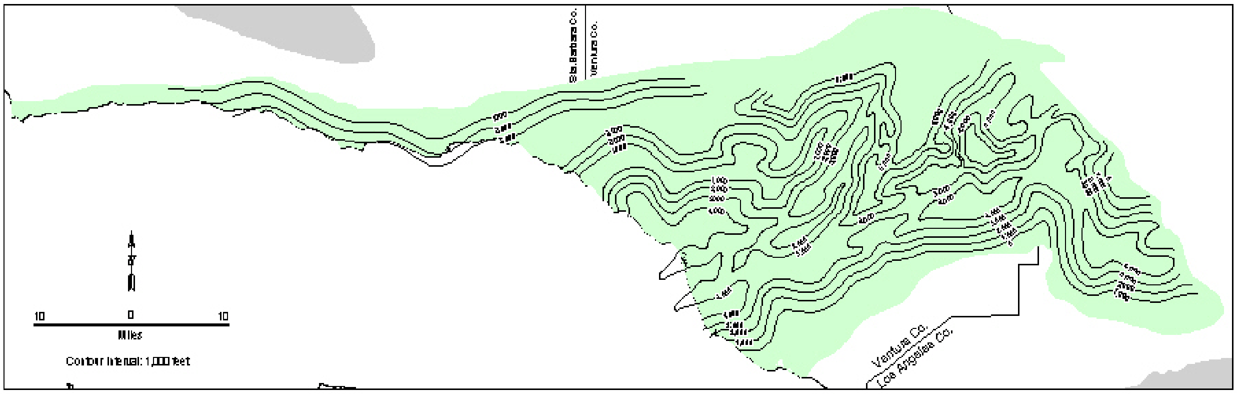

Figure 5. Generalized sandstone isopach map for the Ventura Basin

The Peninsular Ranges are a series of mountain ranges in southwest coastal California characterized by intervening northwest-trending valleys subparallel to faults branching from the San Andreas Fault zone. The Peninsular Ranges are bordered on the north by the Transverse Ranges, on the west by the Channel Islands, and on the east by the Colorado Desert province. The Los Angeles Basin is the largest of the Peninsular Range basins. It is a structurally complex basin located within the San Andreas Transform system at the intersection of the Peninsular Ranges and Transverse Ranges. It covers about 3,890 km^2 (1,500 mi^2) and is bordered on the north by the Santa Monica-Hollywood-Raymond Hill Fault Zone and the Santa Monica Mountains; on the northeast by the Sierra Madre Fault and the San Gabriel Mountains; on the east and southeast by the Chino Fault, Santa Ana Mountains, and the San Joaquin Hills; and on the west and southwest by the Palo Verdes Fault. The basin contains a thick section of primarily Miocene and Pliocene sedimentary rocks estimated to be over 8,200 m (27,000 ft) thick. A generalized cross section is shown in Figure 6. The basin is considered the world's richest in terms of hydrocarbons per unit volume of sedimentary fill and contains three supergiant fields—the Wilmington, Huntington Beach, and Long Beach fields. Major oil-producing formations include the Puente and Repetto sandstones, with porosities ranging from 15% to 35% and permeabilities ranging from 10 to 3,200 md (DOGGR 1991). Porosity and permeability decrease with depth.

A sandstone isopach map for the Los Angeles Basin (Figure 7) indicates that more than 1,520 m (5,000 ft) of sandstone is present within the isopach interval in the central basin, and that sandstone thickness generally correlates with relative basement depth. The thicker sandstone reflected in the basin center is dominated by Puente, Repetto, and Pico formation sandstones but, in the shallower basin margins, the Topanga Formation and older units become locally important in the mapped interval.

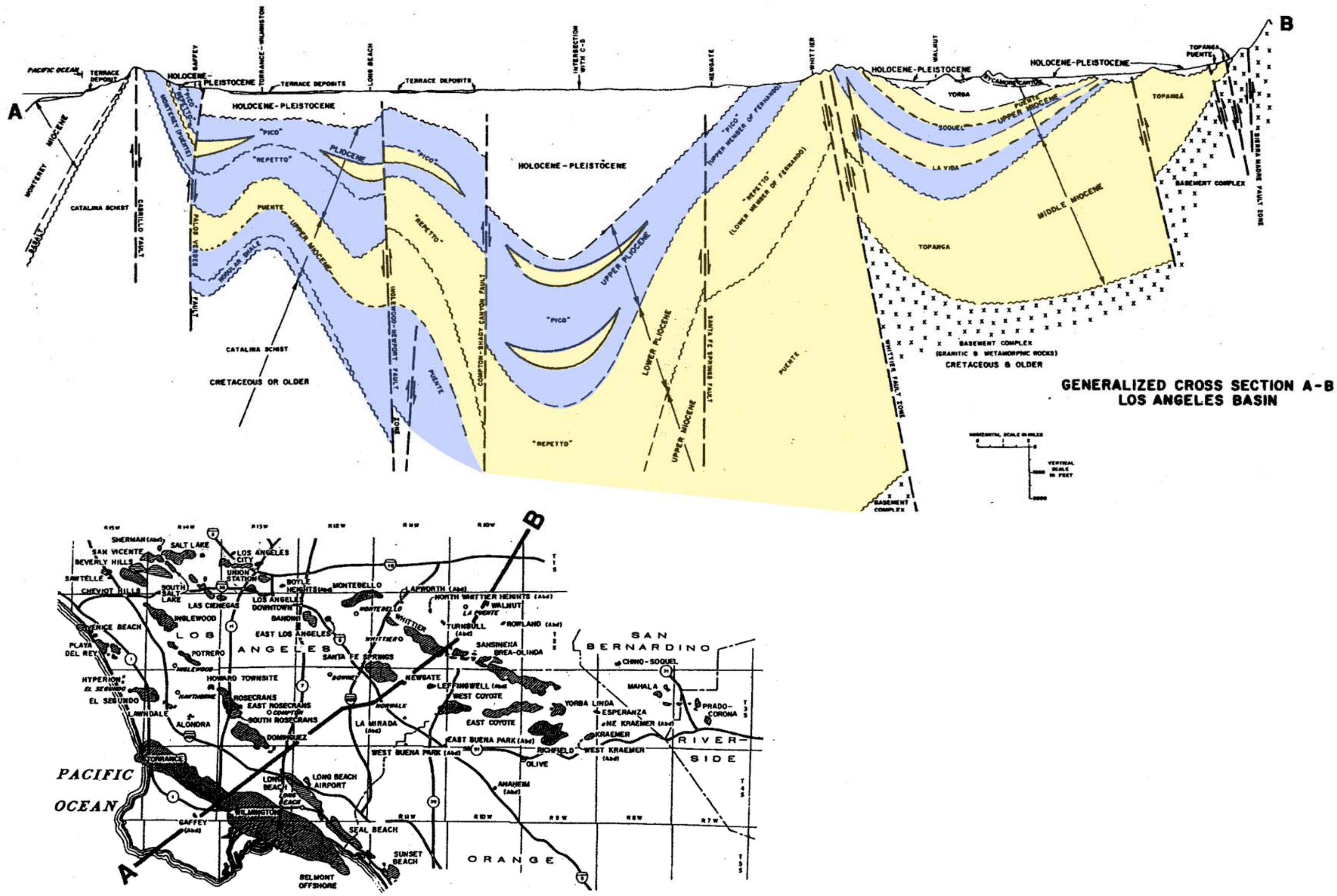

Figure 6. Generalized cross section through the Los Angeles Basin (adapted from DOGGR 1991)

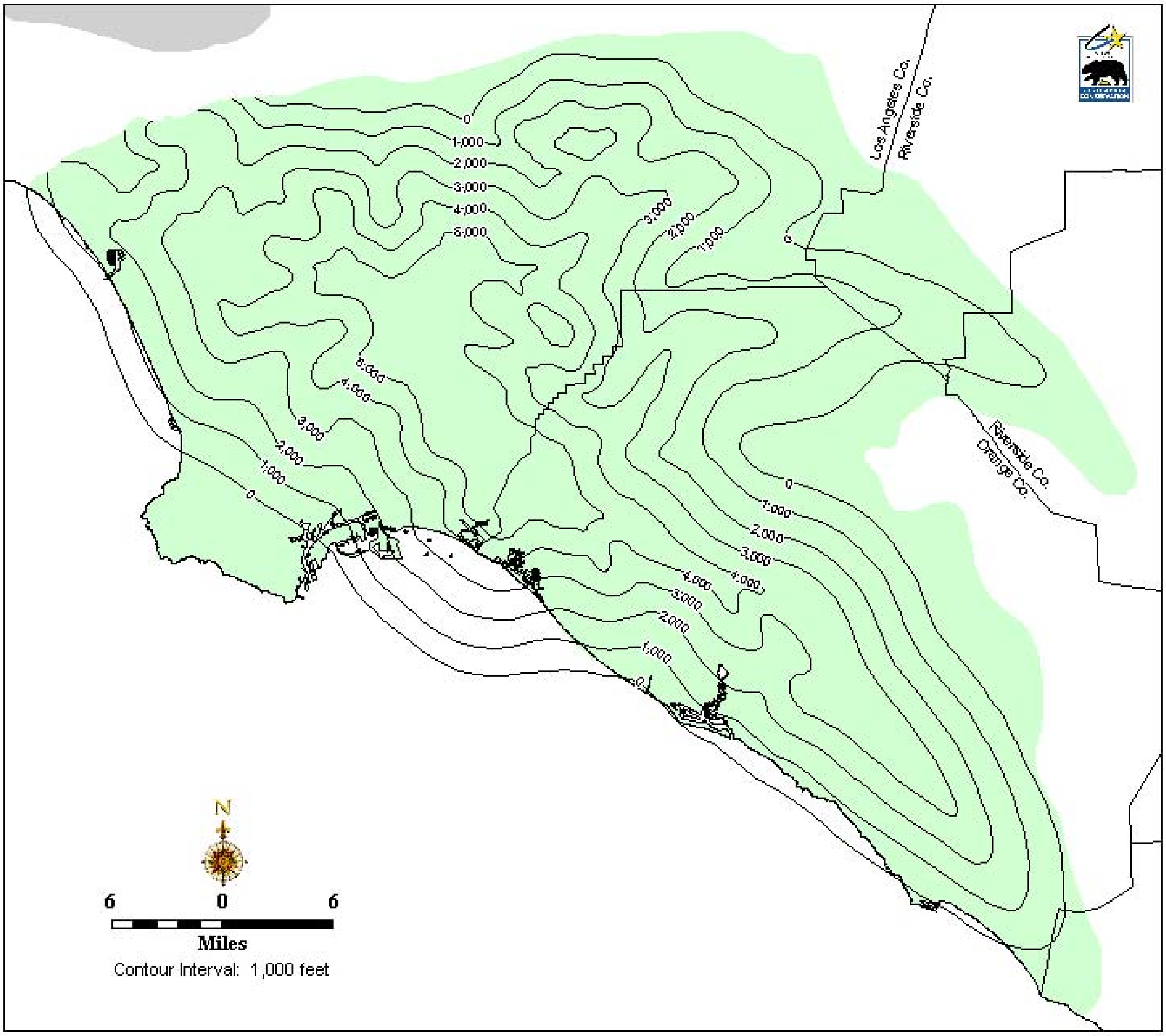

Figure 7. Generalized sandstone isopach map for the Los Angeles Basin

The Eel River, Livermore, Orinda, La Honda, Salinas, and Cuyama marine basins are all found in the Coast Ranges. California's Coast Ranges are composed of a series of northwesterly trending coastal mountain ranges and valleys extending southward from the Oregon state line to the Transverse Ranges in Santa Barbara and Ventura counties. To the east, they are bounded by the Coast Range Thrust, along which older Mesozoic rocks are thrust over Cretaceous rocks of the Great Valley Sequence in the Sacramento and San Joaquin basins.

The Eel River Basin, located in Humboldt County, is the onshore expression of a much larger offshore Cenozoic forearc basin. The onshore portion is expressed as a westerly plunging syncline. While the Freshwater Fault technically bounds the basin on the northeast, its northeast margin is more practically defined by the northeasterly dipping Little Salmon Thrust Fault. To the south, the basin is bounded by the Russ Fault, north of which the upturned beds of the

Yager Formation and lower Wildcat Group are exposed. The basin contains more than 3,800 m (12,500 ft) of sedimentary fill, including over 3,350 m (11,000 ft) of dominantly Neogene marine, sandstone, siltstone, and shale resting on sandstones, conglomerates, and shales of the Cretaceous Yager Formation. Sandstones in the Bear River Beds through Rio Dell Formation may provide carbon sequestration opportunities in the deeper parts of the basin, on anticlinal closures and flanking stratigraphic pinch-outs. While individual sandstones are generally thin, a sandstone isopach map reveals a northwesterly trending zone of sandstone in excess of 760 m (2,500 ft) thick paralleling the north flank of the basin (Figure 8). Enclosing siliceous mudstones and shales should provide seals. Porosities of the sandstones range from 12% to 30% and permeabilities range from 1 md to over 300 md (Stanley 1995b; DOG 1983).

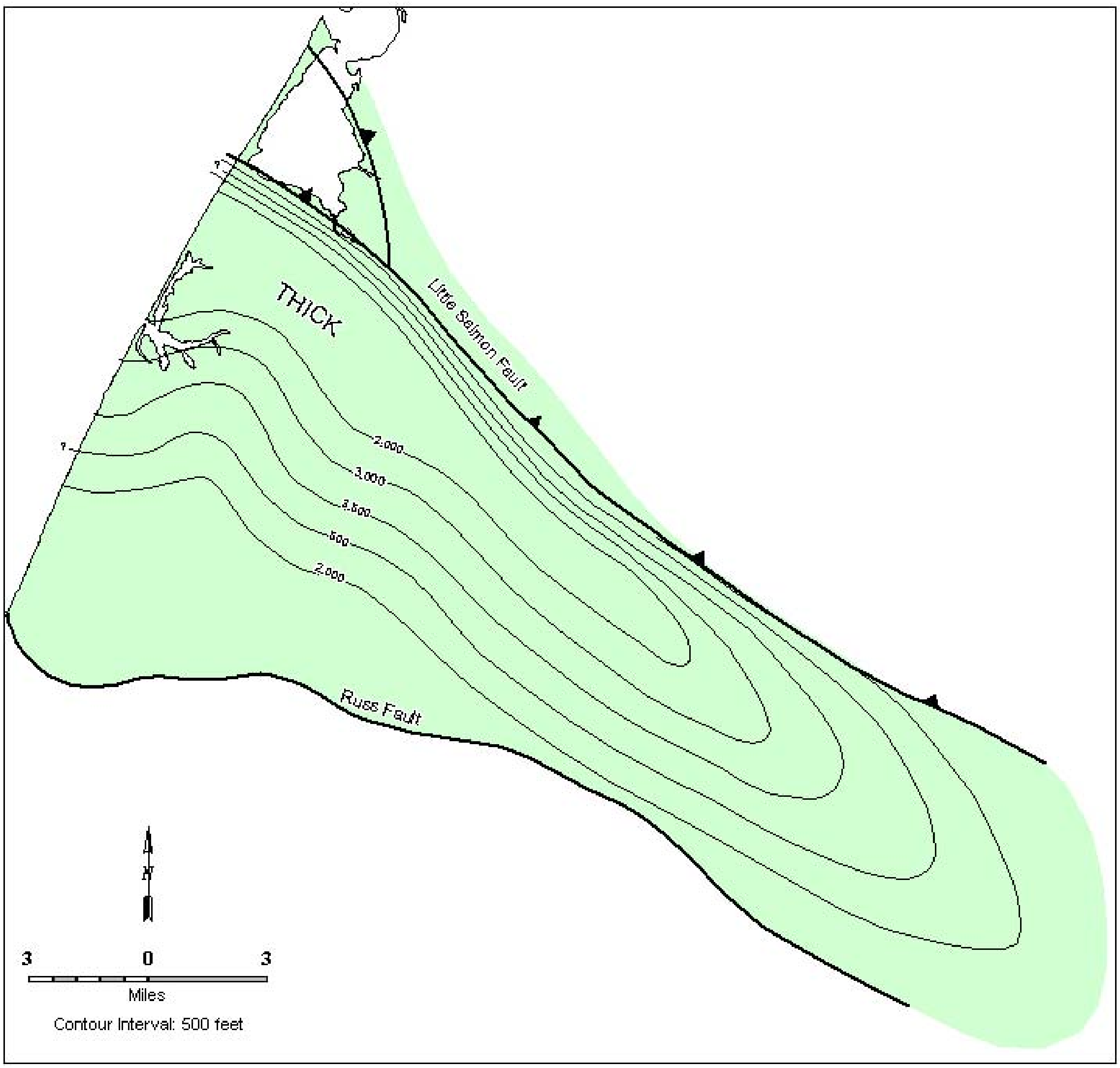

Figure 8. Generalized sandstone isopach map for the Eel River Basin

The Salinas Basin is one of several hydrocarbon-producing Cenozoic marine sedimentary basins west of the San Andreas Fault, including the La Honda Basin to the northwest and the Cuyama Basin to the southeast. The basin is a narrow, northwest-trending feature extending almost 225 km (140 miles) from Monterey County southeastward into San Luis Obispo County, and varying in width from less than 16 to 48 km (10 to 30 miles). It is bordered on the east by the San Andreas Fault. To the northeast, the basin narrows where Salinian granitic basement rocks are uplifted and exposed in the Gabilan Range. The western basin margin is defined by the Jolan-Rinconda Fault Zone and uplifted granitic and metasedimentary rocks of the Santa Lucia Range. The structural and lithologic framework of the Salinas Basin consists of a series of tectonic basement blocks assembled during a complex history of subduction and transform motion along plate boundaries.

The Monterey formation sandstones are hydrocarbon producers and are potential sequestration targets in the Salinas Basin. Porosities in the shallow sands range from 15% to 39% with permeabilities of 500 to 8,000 md (DOGGR 1991). While the Monterey sands in the known oil fields are too shallow for potential sequestration purposes, deeper Monterey sandstones exist farther west in the deeper basin. A gross sandstone isopach map (Figure 9) shows sandstone developments thickening to over 760 m (2,500 ft) to the southwest towards the basin axis. Underlying poorly known lower-middle Miocene and Cretaceous sandstones may also be present at depth.

The La Honda Basin is located north of the Salinas Basin in Santa Clara and Santa Cruz counties between San Francisco and Monterey Bay. The basin is bounded on the northeast by the San Andreas Fault, on the northwest by granitic rocks of Montara Mountain, on the southwest by the Zayante-Vergeles Fault, and on the west by the San Gregorgio–Hosgri Fault (Stanley 1995a). The relatively small basin comprises about 930 km^2 (360 mi^2) and represents a small sliver of the larger San Joaquin Basin, which was displaced approximately 298 km (185 miles) by right lateral slip along the San Andreas Fault. It is estimated that as many as 14,600 m (48,000 ft) of Tertiary sedimentary and volcanic strata fill the basin.

In the eastern basin, the Butano and Locatelli formations are too shallow to be considered for CO_2 sequestration. Westward, towards the basin center, however, sandstone in the Butano and younger formations thickens markedly (Figure 9). The deepest well in the basin, drilled on the Butano Anticline, bottomed in the Butano Formation at 3,370 m (11,053 ft) and encountered more than 1,220 m (4,000 ft) of Butano sandstone within the isopach interval. The Vaqueros through Santa Margarita formations are blanketed by the Santa Cruz Mudstone and Purisima Formation, which can attain thicknesses of 2,700 m (8,900 ft) and 2,400 m (7,900 ft), respectively. Shallow producing sands in the Butano between 550 and 760 m (1,800 and 2,500 ft) deep exhibit porosities between 15% and 35% with permeabilities of 30 to 40 md, but at depth, these are expected to be considerably reduced. Shallow Purisima sandstones between 240 and 820 m (800 and 2,700 ft) deep exhibit porosities of 22% to 34% and permeabilities of 1 to 40 md (DOGGR 1991).

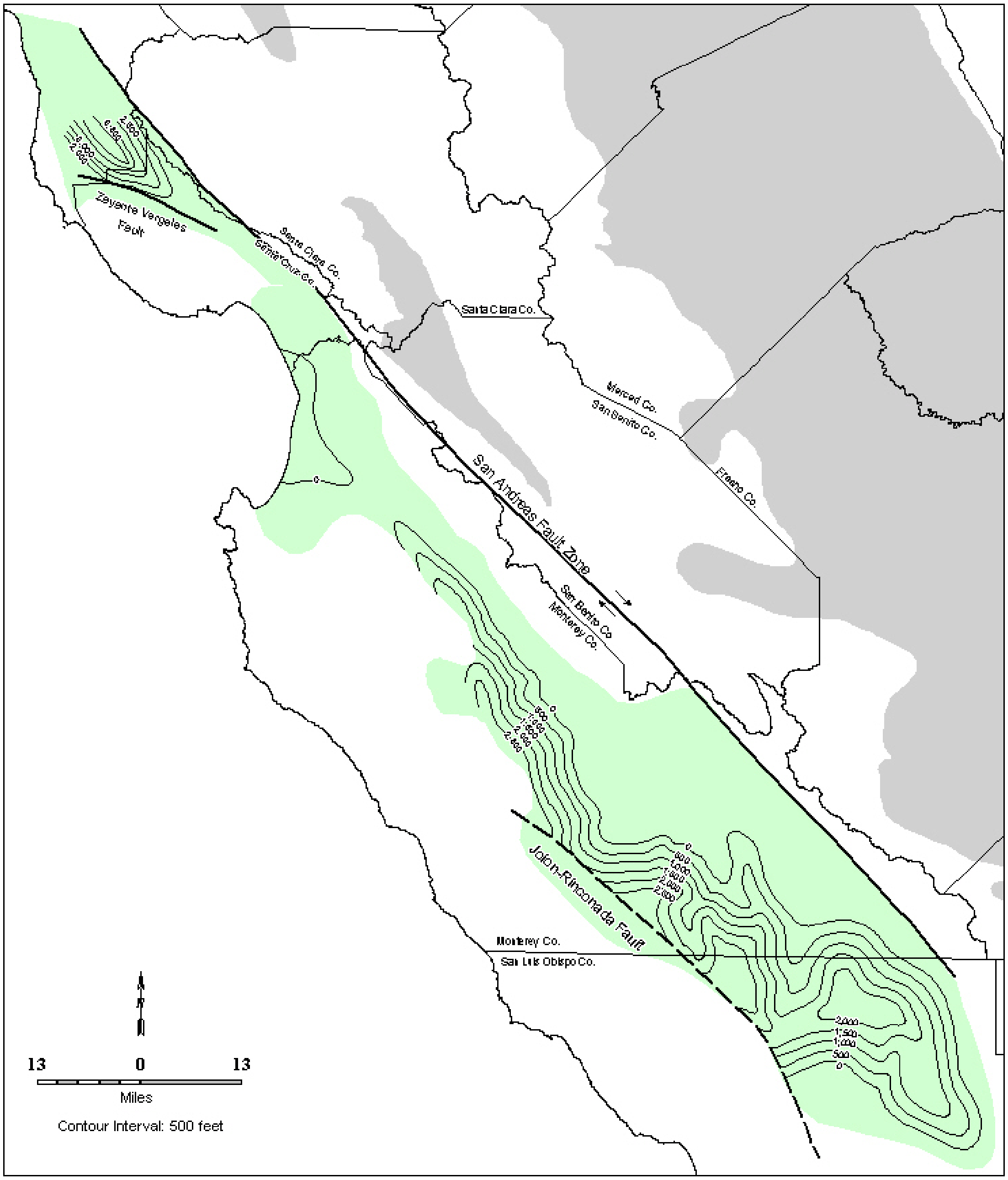

Figure 9. Generalized sandstone isopach map for the Salinas and La Honda Basins

The Cuyama Basin is a relatively small Cenozoic marine basin near the southern end of the Coast Ranges. It extends approximately 105 to 121 km (65 to 75 miles) in a northwest-southeast direction and varies from 13 to 29 km (8 to 18 miles) wide. It is bounded on the northeast by the San Andreas Fault zone and the Temblor Range, which separate it from the San Joaquin Basin. Its southwest margin is structurally complex and consists of at least two lower Miocene wrench faults (Russell and La Panza Faults), which separate the basin from the Sierra Madre Range. The northwest end of the basin is indeterminate, but approaches the southeast end of the Salinas

Basin. Its southeastern end is defined by a buried normal fault subparallel to the younger Big Pine Fault (Tennyson 1995). The basin is structurally complex, with extensive normal faulting of the pre-Pliocene section followed by later thrust faulting of the basement through the Pliocene section, burying much of the sedimentary section below complex thrust sheets.

In the north-central portion of the Cuyama Basin, where deep well control exists, a sandstone isopach map (Figure 10) indicates an area of thick sandstone exceeding 1,220 m (4,000 ft) and aligned in a northwest-southeast orientation roughly paralleling the basin axis. Sandstones within the isopach interval include Branch Canyon and Painted Rock sandstones and overlying Santa Margarita sandstones. Porosities of the sandstones range from 19% to 40%, and permeabilities range from 177 to 1,300 md (DOGGR 1991).

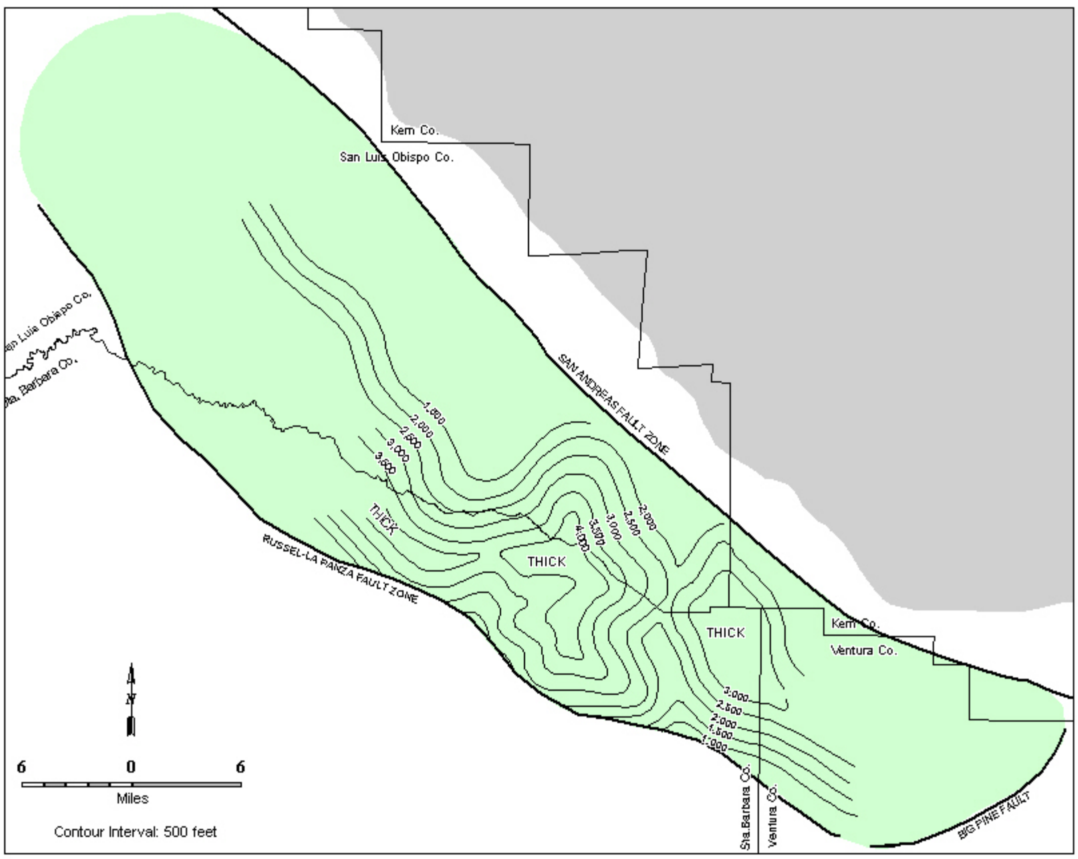

Figure 10. Generalized sandstone isopach map for Cuyama Basin

The Livermore and Orinda basins are part of a related series of deep, linear, Neogene pull-apart basins within the Coast Ranges between San Francisco Bay and the Sacramento Basin. Both basins formed under the influence of extensional stresses after the onset of strike-slip motion along the San Andreas and associated Calaveras and Hayward fault systems during the middle Miocene. The Livermore Basin is approximately 48 km (30 miles) long by 19 km (12 miles) wide. It is bounded on the north and east by Mount Diablo and the Diablo Range, and on the west and southwest by the Calaveras Fault, which separates it from the Orinda Basin. Uplifted Franciscan Complex rocks form its southern end. While the deepest well drilled bottomed at 5,306 m (17,404 ft) in Miocene sediments (Darrow 1979), outcrop and unpublished geophysical data suggest that the Livermore Basin may be filled with as much as 6,700 m (22,000 ft) of Eocene, Miocene, and Pliocene sediments that have been extensively folded and faulted by later compressional forces caused by motion on the marginal faults.

A gross sandstone isopach map for the basin depicts an area of thicker sand development exceeding 490 m (1,600 ft) in the south central portion of the basin (Figure 11). Given the complex structural configuration of the basin, steep dips, and fault displacements along the basin margins, the isopach interval includes sandstones of the Cretaceous Panoche through Pliocene Orinda formations. Limited data on porosity and permeability yield values of about 25% and 250 md, respectively (DOG 1983).

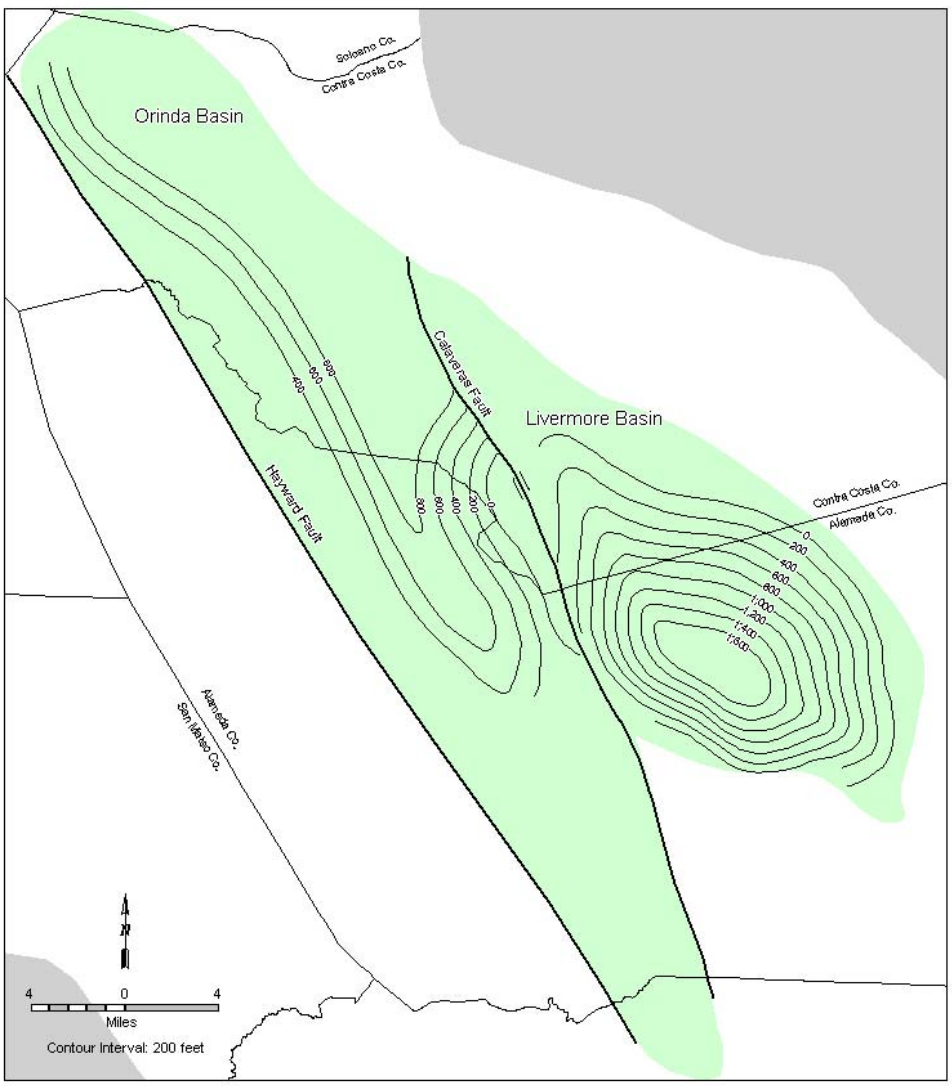

Figure 11. Generalized sandstone isopach map for Livermore and Orinda Basins

The Orinda Basin is a narrow linear basin measuring about 81 km (50 miles) by 11 km (7 miles), bounded on the west by the Hayward Fault and on the east by the Calaveras Fault. Its southern limit is the convergence of the two faults in northern Santa Clara County. Its northern end is taken to San Pablo Bay, past which the Sonoma Basin begins. Limited well control and outcrop data indicate the Orinda Basin contains a sedimentary section very similar to that of the neighboring Livermore Basin. The deepest well bottomed at 3,048 m (9,997 ft) in the abandoned one-well Pinole Point Field near the north end of the basin. Only two other wells exceeded 2,700 m (9,000 ft) with a handful going to 1,500–2,100 m (5,000–7,000 ft). The available well logs were used to construct a sandstone isopach map of logged section, which suggests a longitudinal thickness of at least 240 m (800 ft) extending from near the basin center to San Pablo Bay (Figure 11).

3.1.2. Capacity Assessment

Isopach and depth-to-basement maps were used to estimate the total storage capacity within saline formations in the ten largest sedimentary basins. Table 4 provides the data used to calculate the total available pore volume in the basins. Only a portion of the total pore volume is available for storage. The storage capacity is determined from the mass of CO_2 trapped in the pore space either as a separate phase or dissolved in the pore water.

Table 4. Data used to calculate the pore volume of the 10 largest basins in California

Volumetric Data for California Basins			
	Area (sq. miles)+	Estimated Average Thickness in m (ft)*	Estimated Average Porosity**
Sacramento-San Joaquin basins	18,550	610 (2,000)	0.25
Los Angeles Basin	1,341	920 (3,000)	0.25
Ventura Basin	1,450	920 (3,000)	0.24
Salton Trough	2,559	610 (2,000)	0.24
Eel River Basin	175	460 (1,500)	0.26
Salinas Basin	1,343	460 (1,250)	0.28
La Honda Basin	268	460 (1,500)	0.25
Livermore Basin	144	240 (800)	0.23
Orinda Basin	296	180 (600)	0.23
Cuyama Basin	582	920 (3,000)	0.27

+Area of basin at depths greater than 800 m (2,625 ft)

*Average sands (isopachs) thickness for depth window 800–3,050 m (2,625–10,000 ft)

**Approx. average porosity for all zones in depth window

Many factors affect the percentage of the pore space that could be occupied, including formation heterogeneity, buoyant flow, hydrologic boundary conditions, residual saturation, and other two-phase flow properties. Reservoir modeling studies also suggest that, because of two-phase conditions and diffusion, the pore volume containing dissolved CO_2 will be greater than the pore volume of separate-phase CO_2. Two other factors affecting storage capacity are the density of the in-place CO_2 and the salinity of the pore water. Formation temperature and allowable injection pressures will, in large part, determine the CO_2 density. Salinity of the pore waters is important because CO_2 solubility decreases with increasing salinity.

Figure 12 shows the results of capacity calculations for the ten largest basins in California. Results show total storage capacity for the 10 basins ranging from approximately 75 Gt to approximately 300 Gt of CO_2. The low end of this range would provide sufficient capacity for storing about 500 years of utility and industrial sector emissions at current emission rates. Table 4 shows that more than half of this capacity is contained in the Sacramento–San Joaquin basins.

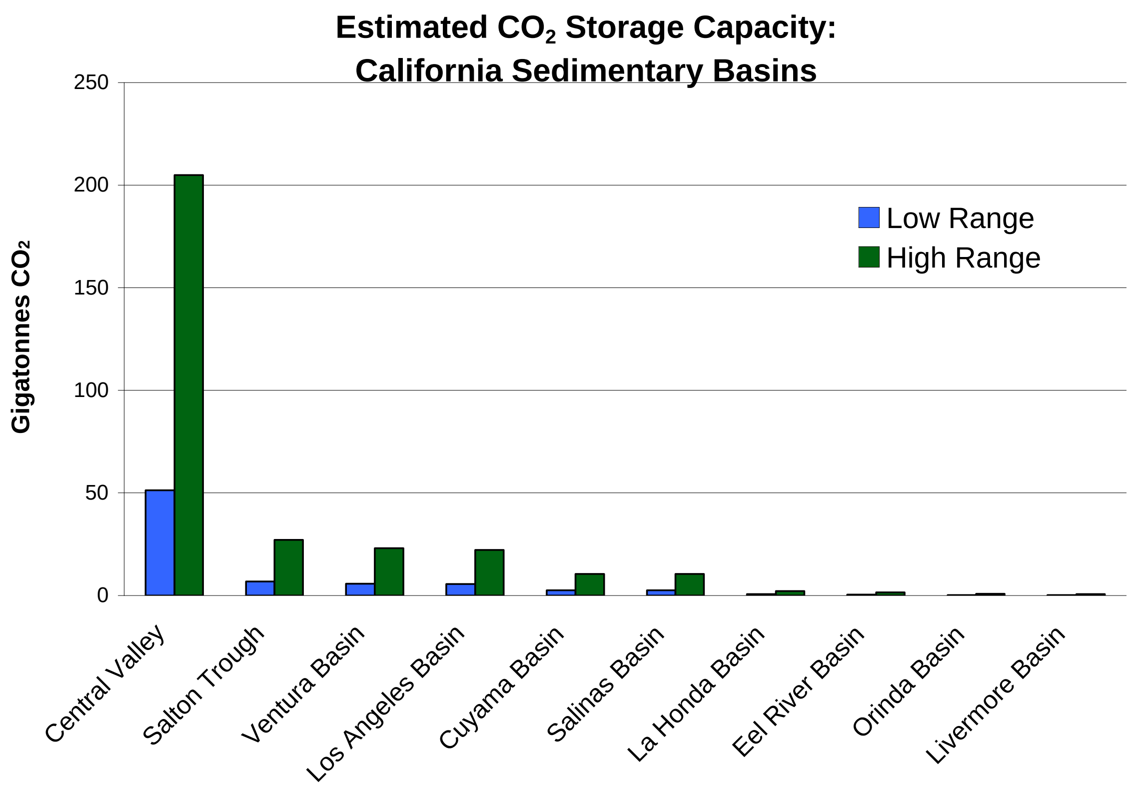

Figure 12. Total CO_2 sequestration capacity of saline formations in the 10 largest basins in California. Capacities were estimated using basin area (>800 m deep), estimated average sand (isopach) thickness for depth window 800–3,050 m, estimated average porosity, and density of CO_2 in the basins equal to 700 kg/m^3. The low-range values correspond to utilization of 1% of the available pore volume, and the high-range values to utilization of 4% of the available pore volume. The Central Valley comprises the Sacramento and San Joaquin basins.

Several of the sedimentary basins, notably the Sacramento, San Joaquin, Los Angeles, and Ventura basins, also contain major oil and gas fields, which will likely be the first targets for geologic sequestration. Estimates for the CO_2 storage capacity of California oil and gas fields were based upon production data using Elewaut et al. 1996:

$$Q_{CO2} = (V_{Uoil} + V_{Ugas}) * \rho_{CO_2} / 1{,}000 \tag{1}$$

where

Q_{CO2} = CO_2 storage capacity ($MtCO_2$).

V_{Uoil} = underground volume of oil produced in mega cubic meters (M m^3).

V_{Ugas} = underground volume of gas produced (M m^3).

ρ_{CO_2} = CO_2 density at the reservoir pressure.

The underground volume of oil and gas was estimated from:

$$V_{Uoil} = V_{oil(st)} * B_o \tag{2}$$

$$V_{Ugas} = V_{gas(st)} * B_g \tag{3}$$

where

$V_{oil(st)}$ = Volume of oil at standard conditions (M m^3).

$V_{gas(st)}$ = Volume of gas at standard conditions (M m^3).

B_o = Oil formation volume factor (FVF).

B_g = Gas formation volume factor (E^{-1}).

A default FVF of 1.2 was applied for oil. The gas expansion factor E was calculated with linear relation: E = 4.8P+93.1, where P is the reservoir pressure in MPa. If the original reservoir pressure value was missing, it was calculated from the average depth of the field, assuming a gradient of 10.5 MPa/km.

An estimate of the CO_2-EOR potential for oil fields was made based on API gravity data and depth. Oil fields at depths greater than 915 m (3,000 ft) and with API gravity more than 25° were classified as fields with miscible CO_2-EOR potential. Fields at depths greater than 915 m (3,000 ft) and with API gravity between 17.5 degrees (º) and 25º were classified as fields with immiscible CO_2-EOR potential. Fields at depths greater than 915 m (3,000 ft) and API gravity less than 17.5º were classified as fields with storage potential but no EOR potential. The attributed GIS database was interrogated using these criteria, yielding 121 fields in California with miscible CO_2-EOR potential and a CO_2 storage capacity of 3.4 Gt. The storage capacity was increased to 3.8 Gt by including the fields in the remaining two categories. Though tiny compared to the total saline formation capacity, the storage capacity associated with potential CO_2-EOR is still equal to over 27 years of current utility and industrial sector emissions.

The capacity of California gas fields, screened by depth, was also estimated using the expression in Equation 1. The result yielded 128 gas fields with a combined storage capacity of 1.8 Gt. Oldenburg et al. (2001) have shown that CO_2 can be used to enhance production from depleting gas fields (EGR), though an estimate of the CO_2-EGR potential for California has yet to be done.

3.2. Oregon and Washington

3.2.1. Sedimentary Basins

In Oregon and Washington, the most promising near-term sedimentary basin targets are found in the Coastal Ranges and Puget-Willamette Lowlands geomorphic provinces, though several interior basins may also be important because of the location of large emission sources (Figure 13). The Coastal Ranges and Puget-Willamette Lowlands provinces are the home of a major Tertiary sedimentary belt of basins that formed in a regional fore-arc environment as the Juan de Fuca Plate subducted beneath the North American Plate. These basins, the boundaries of which are uncertain at this time, are characterized by up to 6,100 m (20,000 ft) of Tertiary sedimentary rocks deposited in embayments and shallow seas. Results for these basins are summarized in the following pages. More detailed information on these as well as other basins in Oregon and Washington is found in Golder Associates 2007.

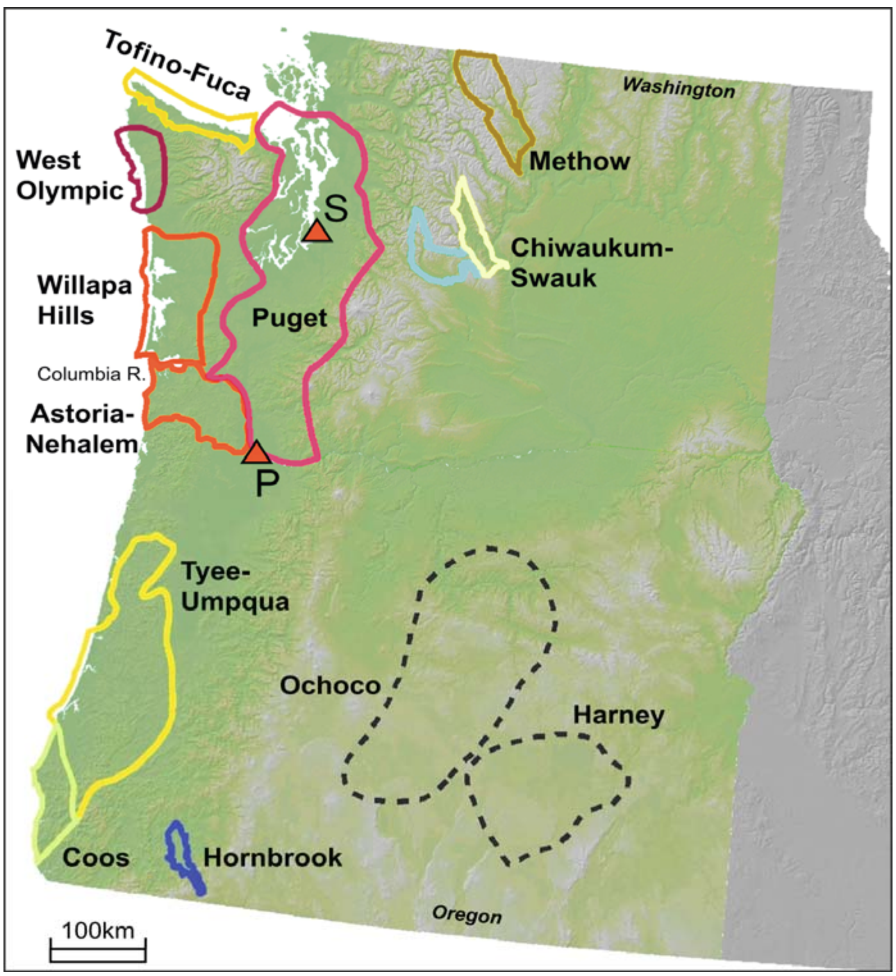

Figure 13. Sedimentary basins in Oregon and Washington. S = Seattle, Wash.; P = Portland, Oreg.

Three basins are found in the Coastal Ranges of Washington: Tofino-Fuca Basin, Western Olympic Basin, and Willapa Hills Basin. Of these, the Western Olympic and Willapa Hills Basins are the most promising. The Western Olympic Basin is located directly west of the Olympic Mountains in Clallam and northern Jefferson Counties, and extends westwards offshore for at least 40 miles (Wagner and Batatia 1985). As seen in Figure 14, the sedimentary strata have an estimated total thickness of at least 2,700 m (9,000 ft), and the recognized formations are:

- Quinault Formation—Pliocene-Miocene (PLMn), up to 1,500 m (5,000 ft) of nearshore sedimentary rocks (siltstone, sandstone and conglomerate).
- Hoh Assemblage—lower-mid Eocene, a sequence of marine rocks accreted to the continental margin:
    - Lincoln Creek Formation—Oligocene-Eocene; up to 2,700 m (9,000 ft) of massive sandstones and tuffaceous siltstones.
    - Skookumchuck Formation—mid-upper Eocene, up to 1,100 m (3,500 ft) of interbedded shallow marine and continental facies (arkosic sandstones and siltstone), and coal in upper and lower member.
    - McIntosh Formation—mid-upper Eocene, up to 1,500 m (5,000 ft) of tuffaceous sedimentary rocks.

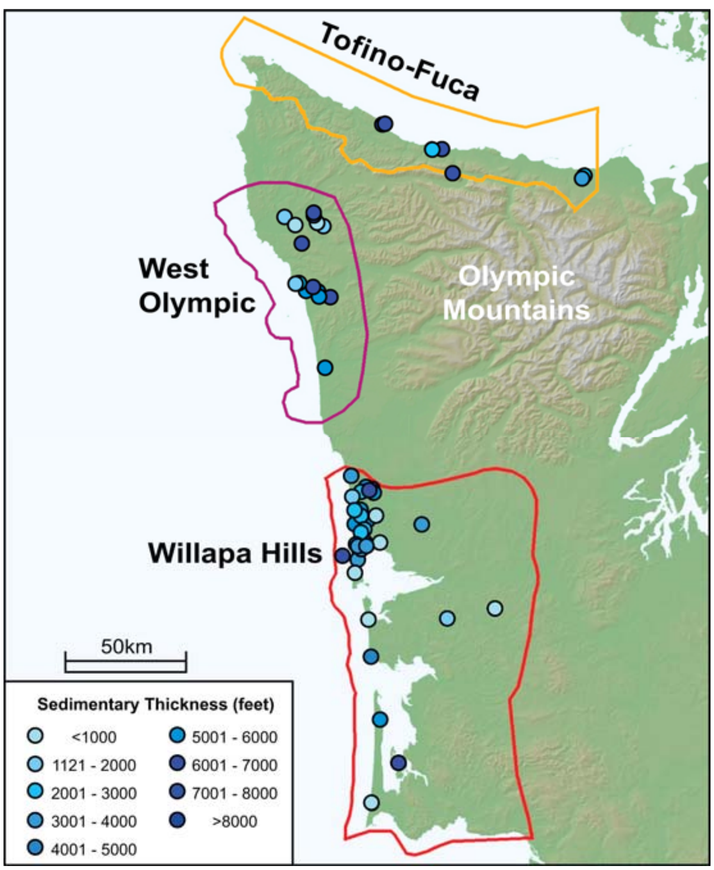

Figure 14. Sediment thickness in basins of Coastal Ranges of Washington

The basin is tectonically active and the sediments are highly deformed; some structural traps are present. The sandstones have porosities of 36%–46% and permeabilities of 102 to 917 md.

The Willapa Hills Basin comprises topographic hills that rise to about 950 m (3,100 ft) above sea level and are situated between the Olympic Mountains to the north and the Columbia River to the south. The Willapa Hills (Grays Harbor) Basin, shown in Figure 14, contains up to 4,600 m (15,000 ft) of upper Oligocene to Quaternary strata overlying basement/broken mélange of mid-Miocene to early Oligocene age. Eocene and Oligocene sediments consist predominantly of deep-water siliciclastics, and arkosic sandstones; interbedded volcaniclastic sandstones are contained within thick marine shale sequences.

The recognized geologic formations in the basin above the Crescent Formation are:

- Quinault Formation—Pliocene-Miocene (PLMn), nearshore sedimentary rocks (siltstone, sandstone, and conglomerate).
- Montesano Formation—mid-upper Miocene (Mm(2m)), up to 920 m (3,000 ft) of fluvial, lacustrine, brackish water, and shallow marine sediments.
- Astoria Formation—lower-mid Miocene, Mm(1a), up to 1,100 m (3,500 ft) of marine sedimentary rocks (carbonaceous, fine-grained sandstone).
- Hoh Assemblage—similar sequence to that in the Western Olympic Basin.
- Cowlitz Formation—Eocene (En(c) or Tco), unconformably overlies the Crescent Formation and contains marine/non-marine siltstone and sandstone.
- Northcraft Formation—Eocene (Evc(n)), up to 460 m (1,500 ft) of volcaniclastic deposits and lavas.

The Willapa Hills Basin is the most promising Coastal Range basin for hydrocarbon development, and therefore CO_2 storage, because of the deep-water sandstones, thick shales and claystones, and anticlinal traps. Sandstones of the Montesano Formation have porosities of 6.4%–32.7% and permeabilities up to 522 md.

The Puget Trough Basin is located in northwestern Washington, and occupies the generally low-lying region east of the Olympic Mountains and west of the Cascade Mountains. The southern extent of the basin is defined by the mergence of the Cascade Range and Coastal Range in Lewis and Cowlitz counties. The basin consists of up to 1,100 m (3,700 ft) of unconsolidated sediments of Pleistocene age overlying up to 3,050 m (10,000 ft) of Tertiary sedimentary rocks. The geology of the Puget Trough is complex, and interpretation is made difficult by the large volume of mostly glacially derived, unconsolidated sediments. Faulting and folding is abundant, and many active faults are recognized. The faulting has resulted in the formation of several major sub-basins (Figure 15):

- Everett Sub-basin—bounded to the north and south by the North and South Whidbey Island Fault Zones, respectively, and attains a maximum thickness of between 3,050 and 4,300 m (10,000 and 14,000 ft), of which as much as 1,100 m (3,600 ft) is considered to be unconsolidated sediments (Jones 1999).

- Seattle Sub-basin—located south of the South Whidbey Island fault, is bounded to the south by the Seattle fault and uplift, and contains up to 4,600 m (15,000 ft) of sedimentary material, of which up to 1,100 m (3,700 ft) is unconsolidated.
- Tacoma Sub-basin—located south of the Narrows Structure, up to 1,800 m (6,000 ft) thick (610 m, or 2,000 ft, of unconsolidated sediments).
- Chehalis Sub-basin—occupies the southern portion of the Trough, south of the Olympic Gravity Anomaly; the unconsolidated sediment thickness is less than 120 m (400 ft) here.

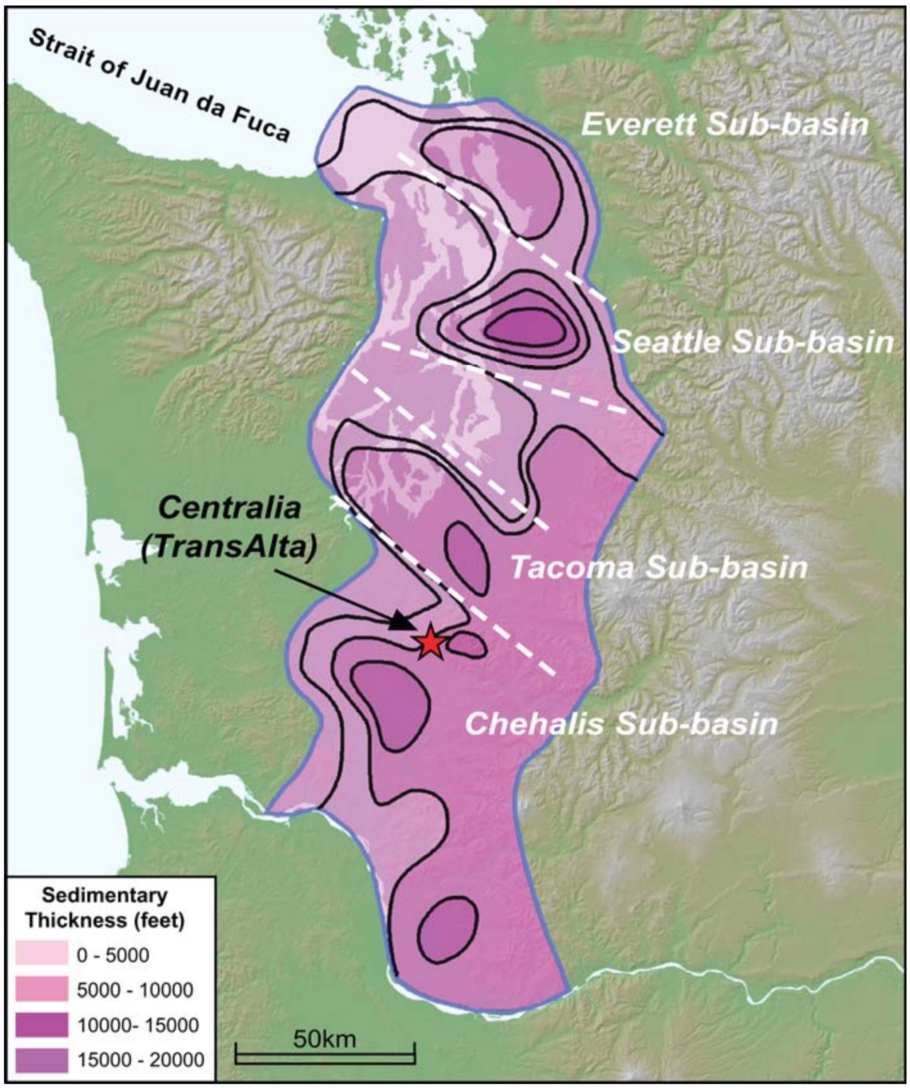

Figure 15. Sedimentary sub-basins in the Puget Trough of Washington. The location of the TransAlta power plant in Centralia, Wash., is noted.

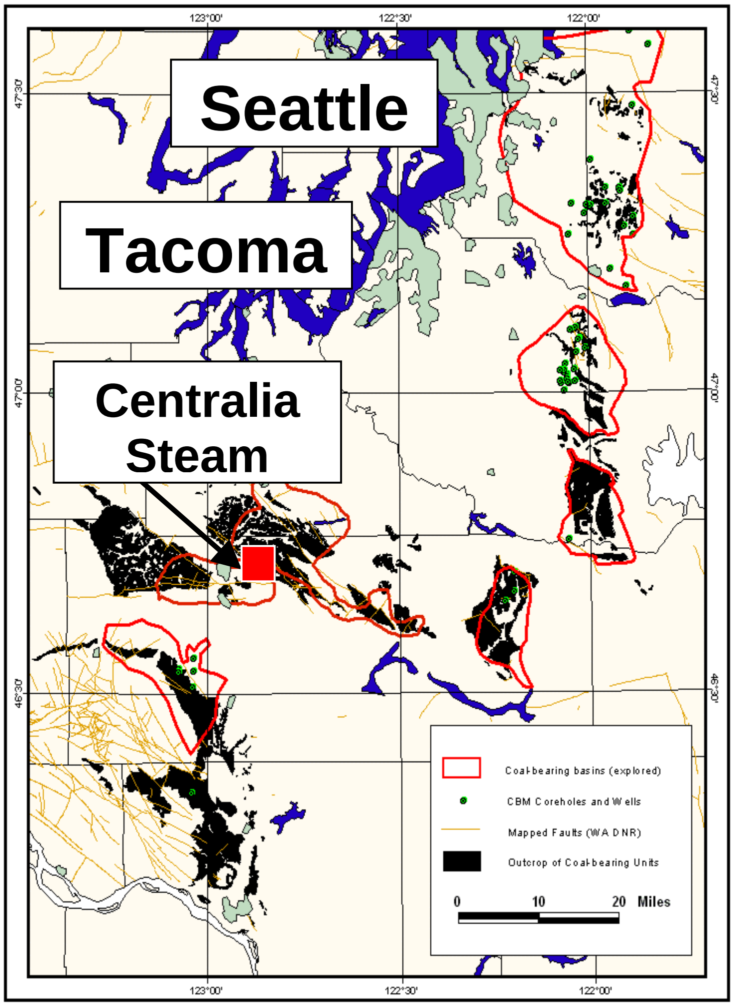

Figure 16. Estimate of extent of coal basins in Puget Trough

The key sedimentary formations in the Everett-Seattle-Tacoma sub-basins are:

- Blakeley and Blakeley Harbor Formations—Oligocene-Eocene (OEm(b)), marine sedimentary rocks in the northern Puget Sound area of interbedded volcaniclastic sandstone, siltstone, shale, and conglomerate.
- Puget Group—Eocene (Ec(2pg)), continental sedimentary rocks/deposits.
- Renton Formation (Ec(2r))—continental sedimentary rocks/deposits (fine- to medium-grained, massive to cross-bedded arkosic sandstone).
- Tiger Mountain Formation (Ec(2t))—continental sedimentary rocks/deposits.
- Tukmila Formation (Evc(t)) – volcaniclastic rocks/deposits (sandstone, siltstone, and conglomerate).

The Chehalis Sub-basin occupies the lowland area between the southern extent of Puget Sound in Thurston County, extending into Lewis County and northernmost Cowlitz County. The basin contains up to 4,600 m (15,000 ft) of sedimentary sequence. The key sedimentary formations are:

- Wilkes Formation—Miocene (Mc(w)), continental sedimentary rocks.
- Hoh Assemblage—lower-mid Eocene, a sequence of marine rocks accreted to the continental margin; includes the Lincoln Creek, Skookumchuck, and McIntosh Formation. Both basal Lincoln Creek Sandstone and Skookumchuck sandstones serve as reservoirs in the Jackson Prairie Gas Storage Field.

Sandstones of the Skookumchuck have porosities of 30% to 38% and permeabilities of 135 to 3,000 md.

The Puget Trough Basin also contains deep coal formations, which are sequestration targets and may have potential for ECBM. Coals in this region occur within the Puget Group. Figure 16 provides an initial assessment of the subsurface extent of the coal basins, showing deep coals to be present over an area of approximately 2,500 km^2. Coal rank (thermal maturity) is an important factor to consider when assessing coal seams for coalbed methane and for sequestration potential. In general, coal rank increases from northwest to southeast in the Puget region, reflecting greater tectonic deformation and heat associated with Cascade Range uplift. Initial analysis indicates excellent coal seam reservoir properties:
30 m (100 ft) coal thickness (in the Skookumchuck formation), 20–24 G(m^3)/ton (700–850 ft^3/ton) CO_2 sorption capacity, and 5 md permeability. The amount of unmineable coal in the Puget Sound Basin was estimated to be over 70 billion tons, with a CO_2 storage potential of 2.8 Gt.

In Oregon, there are three main sedimentary basins in the Coastal Ranges province: Astoria-Nehalem, Tyee-Umpqua, and Coos Basins (Figure 17). They extend beneath the Willamette Lowlands, which separate the Coastal Range and the Cascade Mountains. Definition of the exact extent of each of these basins is problematic because of volcanic and sedimentary cover and tectonic deformation.

The Tyee-Umpqua Basin occupies the southern half of the Coastal Range, extending from a latitude near Salem, beyond Roseburg, to the junction of the Coastal Range with the Klamath Mountains. To the west are the younger basinal sediments of the Coos Basin. The basin consists of more than 6,100 m (20,000 ft) of lower-middle Eocene sedimentary strata preserved in the Coastal Range hills. In fact, the basin contains two superimposed basins with different geologic trends and tectonic histories: the northeast-southwest trending early Eocene Umpqua Basin and the north-south trending Tyee Basin.

The main geologic units identified in the basin are as follows:

- Spencer Formations—lower-mid Eocene, up to 150 m (500 ft) of arkosic sandstone (fluvio-deltaic).
- Bateman Formation—mid-upper Eocene, up to 760 m (2,500 ft) of arkosic sandstone (deltaic) and mudstone.

- Elkton Formation—mid-Eocene, up to 920 m (3,000 ft) of mostly mudstone and minor sandstone.
- Tyee Formation—mid-Eocene, mostly 1,830 m (6,000 ft) of sandstone, deposited in a shallow marine to non-marine deltaic environment (south) to slope and deep marine basinal margin (north). The eastern margin is truncated by younger rocks or covered by younger volcanic rocks; the western margin is a passive sill or a seamount terrane of oceanic crust. Contains several recognized members.
- Umpqua Group—upper Paleocene to lower Eocene, up to 3,050 m (10,000 ft) of mudstone, sandstone, and conglomerate (non-marine to deep marine origin). Prominent formations recognized in reports include the Camas Valley White Tail Ridge, Tenmile, and Bushnell Rock Formations.

For the massive Tyee sandstones, porosity and permeability average 10.8% and 2.76 md, respectively (Ryu and Niem 1999).

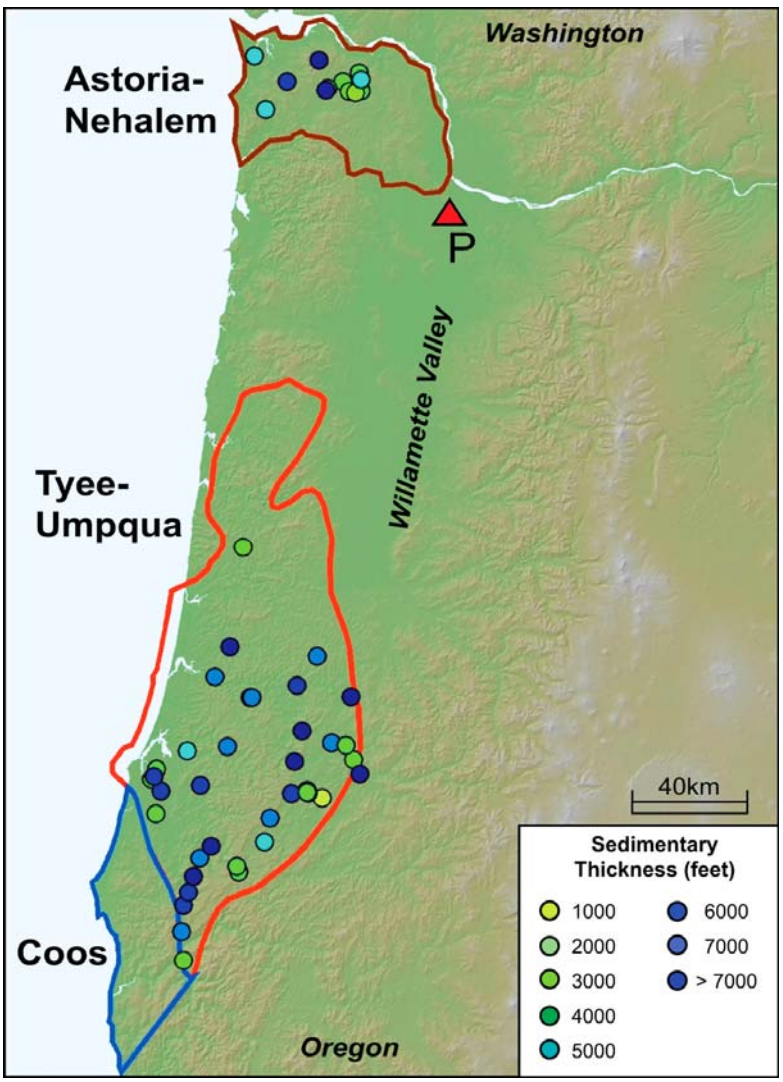

Figure 17. Sedimentary basins and sediment thickness in the Oregon Coastal Ranges. P = Portland, Oregon.

The Coos Basin is located in coastal southwestern Oregon in the Coastal Range Province. The basin extends from the western edge of the Tyee Basin and the Klamath Mountains, and continues offshore. The geology of the basin consists of up to 3,050 m (10,000 ft) of marine sedimentary rocks. The key units are as follows:

- Bastendorff Formation—upper Eocene to lower Oligocene, up to 880 m (2,900 ft) of thinly laminated siltstone and mudstone.
- Coaledo Formation—upper Eocene, up to 1,800 m (6,000 ft) of deltaic sandstones, and prominent coal seams.
- Bateman Formation—mid-Eocene, 300 m (1,000 ft) of sandstone (near-shore, deltaic).
- Tyee Formation—similar strata to those in the Tyee Basin, up to 1,500 m (5,000 ft) thick in the Coos Basin.
- Fluornoy Formation—mid-Eocene, between 300 and 1,500 m (1,000 and 5,000 ft) of sandstone and siltstone sequence.
- Looking Glass Formation—lower Eocene, basal conglomerate and overlying fine-grained sandstone and siltstone sequence (up to 2,100 m, or 7,000 ft, thick.
- Roseburg Formation—lower Eocene-upper Paleocene, between 3,050 and 3,700 m (10,000 and 12,000 ft) of rhythmites and submarine basalts.

Sandstones of the Coalcedo and Fluornoy formations have porosities of 18%–43% and permeabilities of 4.5 to 1,800 md.

The Astoria-Nehalem Basin is located in northwestern Oregon, in western Columbia and eastern Clatsop counties, about 45 miles northwest of Portland. The basin contains the only economically productive gas field (known as the Mist Gas Field) in Oregon. This field occupies an area of about 13 km^2 (5 mi^2) and was first produced from in 1979. The basin geology is complex because of extensive folding and faulting. Normal and strike-slip faulting is common, with the predominant fault trend being northwest; some significant east-west and northeast-southwest faulting also exists. Faulted anticlines are reportedly the most common trap in the Mist Field. The earliest sedimentary unit is the mid-Eocene Yamhill Formation (siltstones and shales). Although the sedimentary units interfinger with the volcanics, the Yamhill does contain a prominent sandstone member. The Cowlitz Formation overlies the Yamhill Formation, and consists of micaceous, arkosic-basaltic marine sandstone, siltstone, and mudstone. Of key importance is the gas-producing Clark & Wilson (C&W) sandstone, which is overlain by a thick shale unit. The C&W sandstones have porosities up to 39% and permeabilities from 1 to 1,400 md. A sequence of marine sedimentary units overlies the Cowlitz Formation and consists of thickly to thinly bedded tuffaceous mudstone, siltstone, and sandstone. Key units include the Spencer, Keasey, Pittsburg Bluff, and Astoria Formations (all mid-upper Eocene).

There are several interior basins in Washington and Oregon that contain sedimentary deposits. Very little is known about the geology and properties of the rocks in these basins, but they could be potentially important for sequestration because of the proximity to power plants. These basins include the Methow, Chiwaukum, Ochoco, and Hornbrook. The Methow Basin contains approximately 4,000 m (13,000 ft) of sedimentary rocks, including several massive sandstones in the Winthrop Formation. The Chiwaukum Basin contains about 5,800 m (19,000 ft) of continental sedimentary sequences. The Ochoco Basin contains more than 1,500 m (5,000 ft) of fluvio-deltaic sandstones and conglomerates, and the Hornbrook Basin contains about 1,200 m (4,000 ft) of sediments. Hornbrook Formation sandstones have porosities of 6.3%–18.6% and permeabilities up to 1.2 md.

3.3. Nevada

In Nevada, ongoing crustal extension is responsible for the current basin and range topography. Essentially every mountain range is bounded on one or both sides by a fault that has been active in Quaternary time (Price et al. 2007). Sediments that have filled the basins between the mountains could provide sequestration targets, but there is generally a paucity of information on the structure and properties of these basin-filling sediments. Figure 18 shows the basins in which fill is greater than 1 km (0.6 mi), based on interpretation of gravity data (Price et al. 2007), with no distinction based on rock type or structure. If all potential screening criteria are applied, the basins with the largest areas of potential for CO_2 sequestration by injection into saline aquifers are Granite Springs Valley in Pershing County, Antelope and Reese River Valleys in Lander County, and Ione Valley in Nye County. Each contains an area of 30 km^2 (12 mi^2) or more. The Nevada Bureau of Mines and Geology (NBMG) has no records of deep (>1,000 m, or >3,300 ft) wells in any of these areas (Price et al. 2007).

NBMG constructed a conceptual model of oil and potential CO_2 reservoirs and seals in Nevada (Figure 19) (Price et al. 2007). NBMG states that oil occurs in two broad types of reservoirs in Nevada: fractured and permeable Paleozoic sedimentary rocks (mostly limestones but locally also sandstones), and fractured Tertiary ash-flow tuffs. The study concludes that permeable, unfractured sandstones may occur in the Paleozoic section and in the Tertiary valley-fill sequences in the basins. Seals for the oil reservoirs and, hence, potential CO_2 sequestration sites, include Paleozoic marine shales, Tertiary lacustrine shales, and the nonwelded clay- or zeolite-altered upper zones of ash-flow tuffs (Price et al. 2007). NBMG concludes that the best seals appear to be above the Paleozoic-Tertiary unconformity.

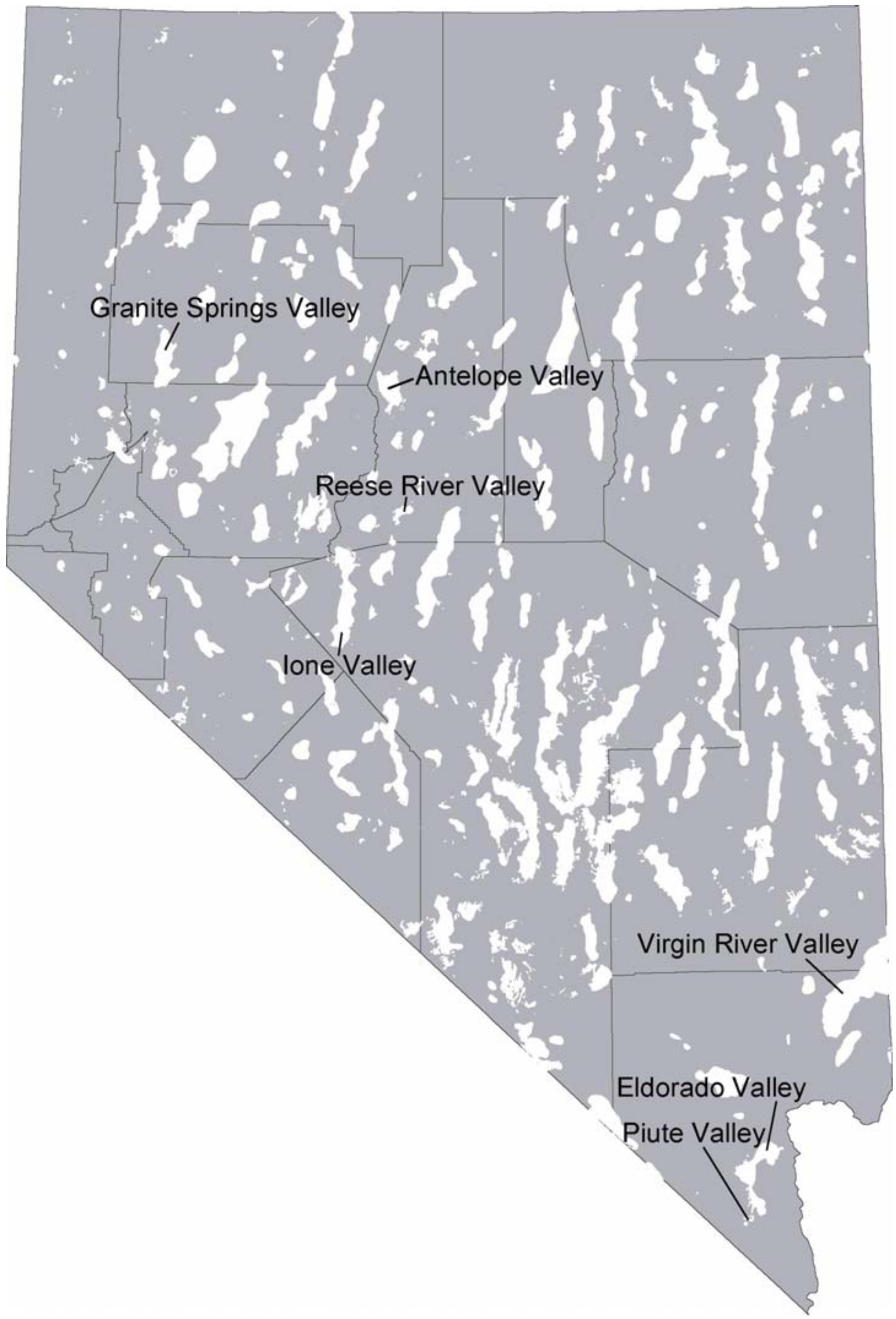

Figure 18. Nevada basins with fill thickness greater than 1 km (Price et al. 2007)

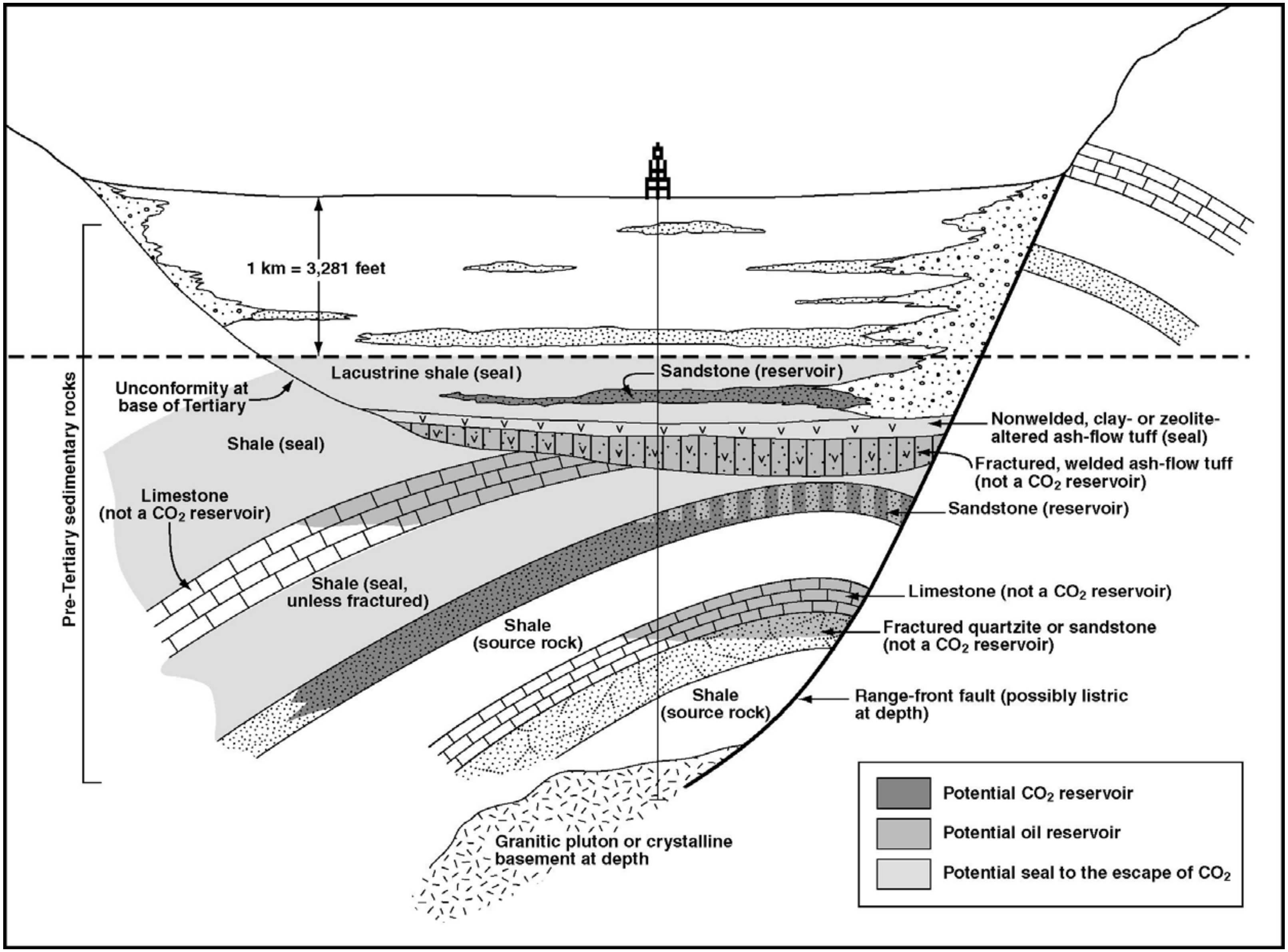

Figure 19. Conceptual model of oil reservoirs and saline formations in Nevada (Price et al. 2007)

4.0 Conclusions

Phase I characterization of regional geological sinks shows that geologic storage opportunities exist in the WESTCARB region in each of the major technology areas: saline formations, oil and gas reservoirs, and coal beds. This characterization work focused on sedimentary basins as the initial most-promising targets for geologic sequestration. GIS layers showing sedimentary basins, and oil, gas, and coal fields in those basins, were developed. The GIS layers were attributed with information on the subsurface, including sediment thickness, presence and depth of porous and permeable sandstones, and, where available, reservoir properties.

California offers outstanding sequestration opportunities because of large capacity and the potential for value-added benefits from EOR and EGR. The estimate of the storage capacity of saline formations in the ten largest basins in California ranges from about 150 to about 500 Gt of CO_2, depending on assumptions about the fraction of the formations used and the fraction of the pore volume filled with separate-phase CO_2. Potential CO_2-EOR storage was estimated to be 3.4 Gt, based on a screening of reservoirs using depth, an API gravity cutoff, and cumulative oil produced. The cumulative production from gas reservoirs (screened by depth) suggests a CO_2 storage capacity of 1.7 Gt.

In Oregon and Washington, sedimentary basins along the coast offer sequestration opportunities. Of particular interest is the Puget Trough Basin, which contains up to 1,130 m (3,700 ft) of unconsolidated sediments overlying up to 3,050 m (10,000 ft) of Tertiary sedimentary rocks. The Puget Trough Basin also contains deep coal formations, which are sequestration targets and may have potential for ECBM.

Nevada might offer geologic sequestration targets in its intermontane basins, but a lack of data on the sediments in these basins makes an estimation of CO_2 storage capacity difficult at this time. The basins with the largest areas of potential include the Granite Springs Valley in Pershing County, Antelope and Reese River Valleys in Lander County, and Ione Valley in Nye County.

More detailed characterization and further refinement of capacity estimates will be carried out in WESTCARB Phase II. In California, this will include developing GIS-based gross sandstone isopach maps for promising CO_2 sinks, including the Starkey, Winters, and Mokelumne River formations, and mapping the associated seals. Preliminary characterization in Alaska will be performed and will include a high-level evaluation of the geologic CO_2 storage potential of sedimentary basins (and associated oil and gas fields and coal basins) and concentrated study on those basins with high sequestration potential. Continuing characterization in Oregon and Washington will include defining the geometry and physical properties of the basins located in the Coastal Range province (Coos, Tyee, Astoria, Nehalem, Willapa Hills, Western Olympic and Tofino-Fuca basins) and the Puget-Willamette Trough, and utilizing these data to estimate their potential CO_2 storage capacities. Nevada research will include an investigation of the potential for geologic sequestration using mafic and ultramafic rocks and enhanced oil recovery. Finally, the partnership will perform a preliminary characterization of the potential for geologic sequestration in the offshore subsurface environment in California, Alaska, Oregon, and Washington.

Benefits to California

This research provides benefit to California's electricity ratepayers by assessing the potential for geologic sequestration of CO_2 in the state of California and in nearby states from which California does and may, in the future, obtain electric power. As noted by this report, geologic sequestration in California alone could potentially offset a significant portion of California's stationary source greenhouse gas emissions—between ~80 and 305 Gt CO_2, which equates to over two thousand years' worth of the state's large stationary source emissions.

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6.0 Glossary

CCS	Carbon capture and sequestration
CO_2	Carbon dioxide, a key greenhouse gas associated with global climate change
DOG	Division of Oil and Gas (California Department of Conservation)
DOGGR	Division of Oil, Gas, and Geothermal Reservoirs (California Department of Conservation)
ECBM	Enhanced coal bed methane recovery
EGR	Enhanced gas recovery
EOR	Enhanced oil recovery
GIS	Geographic Information System
Gt	Gigatonne (10^9 metric tons), a commonly used unit for measuring carbon dioxide
md	Millidarcy, a common unit of measure for permeability
NBMG	Nevada Bureau of Mines and Geology
WESTCARB	West Coast Regional Carbon Sequestration Partnership

Appendix A

WESTCARB Geographic Information System

Appendix A: WESTCARB Geographic Information System

As noted in section 1.2, the WESTCARB Geographic Information System (GIS) is housed in an Enterprise Geodatabase format using ArcSDE (Spatial Database Engine) from Environmental Systems Research Institute, Inc. (ESRI). The data layers can also be downloaded from the Utah Automated Geographic Reference Center (AGRC; http://atlas.utah.gov/WESTCARB-GIS-data/), or viewed via the WESTCARB Interactive Map (http://atlas.utah.gov/co2wc). This appendix is a list of all geologic and associated shapefiles available either via the WESTCARB Interactive Map and/or the data download site. The WESTCARB GIS also includes GIS layers related to terrestrial sequestration; for more information on these layers, visit the URLs noted above.

GEOLOGIC LAYERS

Shapefiles available for viewing via the WESTCARB Interactive Map and download via the FTP site:

- **AK_Oil_and_Gas_Fields**
  Outlines of Alaska's oil and gas fields. Data provided by the Alaska Department of Natural Resources.
- **AK_Sedimentary_Basins**
  Outlines of Alaska's onshore and offshore sedimentary basins. Source data: Kirschner, 1994.
- **AZ_Sedimentary_Basins**
  Sedimentary basins in Arizona determined to be potentially suitable for geologic sequestration
- **BC_Coal_Fields**
  Approximate areal extent of coal bearing strata with potential for coal bed gas development in British Columbia, Canada. Field outlines provided by the British Columbia Ministry of Energy, Mines and Petroleum Resources.
- **BC_Oil_and_Gas_Fields**
  Field outlines of British Columbia's oil and gas fields. Data provided by the British Columbia Ministry of Energy, Mines and Petroleum Resources, Oil and Gas Division.
- **BC_Sedimentary_Basins**
  Areal extent of unmetamorphosed sedimentary rocks in Phanerozoic sedimentary basins only. Produced by Geological Survey of Canada Energy Synthesis Project. Scale 1:5,000,000. From Mossop et al. 2004.
- **CA_Oil_and_Gas_Fields**
  Areal extent, physical rock properties, and production information for California's oil and gas fields

- **CA_Sedimentary_Basins**
  Sedimentary basins in California. Includes “screened” basins, where significant porous and permeable strata, thick and pervasive seals, and sufficient sediment thickness to provide critical-state pressures for CO_2 injection (>800 m (2,625 ft), or >1,000 m in the case of non-producing basins due to data resolution) are present. The maximum depth of characterization of any basin was 3,050 m (10,000 ft.). Also includes “excluded” basins, which are the sedimentary basins that were not considered suitable for CO_2 sequestration.
- **NV_Sedimentary_Basins**
  Sedimentary basins in Nevada, including areas where valley-filling alluvium and volcanic rocks exceed 1 kilometer in thickness (“included”), and areas excluded from consideration for CO_2 sequestration due to basin fill being less than 1 kilometer thick (“excluded”).
- **OR_WA_Consolidated_Basins**
  Known consolidated (lithified) sedimentary basins
- **Lower_48_Coal_Fields**
  This data set shows the coal fields of the conterminous United States. Most of the material for the conterminous United States was collected from James Trumbull's "Coal Fields of the United States, Conterminous United States" map (sheet 1, 1960).

Supporting Data

All supporting data layers are available via direct request from AGRC

- *Alaska Layers*
  - **AK_Fault**
    This digital map database represents the general distribution of major structures, lithologic contacts, faults, folds and gravity anomalies in the state of Alaska and dominant movement along these faults.
  - **AK_GeologicUnits**
    A regional summary of geologic formations and units that can be shown cartographically at 1:2,500,000
- *British Columbia Layers*
  - **basins_bcintersect**
  - **foothills**
  - **TPDR_NEBC**
    Petroleum Development Roads
  - **BOGCZ_BC**
    OGC Administrative Zones

- **AWSH_BC**
  Oil and Gas Well Surface locations for British Columbia
- **TPDR_NEBC**
  Petroleum Development Roads, British Columbia
- **BC_Fault**
  Digital file containing fault lines for British Columbia. Faults are identified by a type attribute.
- **BC_GeologicUnits**
  Polygon coverage of geology compiled at 1:100,000 scale as part of the B.C. Ministry of Energy & Mines, Geological Survey Branch mineral potential project, 1994–1996.

- *California Layers*
  - **CA_BasementMaster**
    Depth-to-basement, California
  - **CA_IsopachMaster**
    Sedimentary fill isopach maps, California
  - **CA_HistoricFault**
  - **CA_HoloceneFault**
  - **CA_LateQuaternaryFault**
  - **CA_PreQuaternaryFault**
  - **CA_QuaternaryFault**
- *Nevada Layers*
  - *CO_2 Model Data Layers*
    data layers used to construct the final model for Price et al. 2007
    - **1K_GOOD**
      Areas indicated by model as meeting criteria
    - **bedrock**
      Bedrock areas from geology map
    - **clip_ha694b**
      Nevada carbonate province outline
    - **faults_final_clip**
      Buffered normal and strike slip faults
    - **fin_md_mm5_120_5k**
      Areas with potential mineral resources

- **geology**
  Nevada 1:500,000 scale geology
- **geotherm20k**
  20k geothermal buffer map
- **k1_basin**
  1 kilometer basin fill or greater
- **nv_boundary**
  Nevada boundary map
- **people**
  Areas of population/transportation effects
- **restricted_lands**
  Areas of withdrawn lands
- **val_fill**
  Valley fill from Geology map
- **vf_shallow**
  Areas of shallow valley fill

- *Original Data Sets*
  Directory containing assorted data sets used to build model data sets for Price et al. 2007. Some data sets are completely documented and others are not.
  - **Cities**
    Cities and Towns in Nevada, from Nevada Bureau of Mines and Geology (NBMG)
  - **geothermal**
    Geothermal locations in Nevada
  - **map120_f**
    Draft updated version of NBMG Map120
  - **mdist_p**
    Mining district map of Nevada, NBMG Report 47
  - **nbmg_qf**
    NBMG Quaternary fault data base
  - **nv_urban_UTM27**
    Nevada urban areas from US Census data
  - **Roads**
    Major Nevada roads and highways
  - **usgs_qf**
    USGS Quaternary faults for Nevada

- *USGS Geologic Map, 500k*
  - **LINES**
    500k Nevada geology - lines
  - **POLYS**
    500k Nevada geology – polygons
- **ofr_04_01**
  Data from "Nevada Oil and Gas Well Database (NVOILWEL)" Compiled by Ronald H. Hess. Assisted by Shane P. Fitch and Sean N. Warren, 2004, Nevada Bureau of Mines and Geology Open-File Report 04-1
- *Data from NBMG Open-File Report 01-03*
  - **nv_mrds**
    USGS MRDS data
  - **mils2000**
    USBM MILS data
  - **dom_aml**
    Div. of Minerals Abandoned Mines 3
  - **nv_pts**
    Prospect, shaft, and tunnel sites
- **cities**
  NBMG cities and Towns in Nevada
- **county_p**
  NBMG county polygon coverage of Nevada
- **nvqdp**
  NBMG 7.5 minute quadrangle boundaries of Nevada
- **roads**
  NBMG major Nevada roads and highways
- **Nev_Base.tif**
  NBMG Georeferenced tifw 1:1,000,000 scale base map of Nevada
- **NV_500k_topo.tif**
  USGS Scanned georeferenced tifw 1:500,000-scale topographic map of Nevada

- *Oregon Layers*
  - **OR_500kFaults**
    This theme shows all known geological faults in Oregon.
  - **OR_500kGeology**
- *Washington Layers*

- WA_100kFaults
- **WA_500kGeology**
  Contacts and lithologic units for the geologic map of Washington
- **WA_100kGeology**
- **WA_100kFolds**
- **WC_QfaultL_25**
  This map layer contains locations and information on faults and associated folds, in the WESTCARB states that are believed to be sources of significant earthquakes (those of magnitude 6 or greater) during the past 1,600,000 years.

- *Oregon and Washington Isopach Layers*
  - *Columbia River Basalt Group Layers—Geoelectric data*
    Digital representation of Magnetotelluric Survey Data in the Pasco area to determine the subsurface geometry of the Basalt Waste Isolation Project
    - **Isopach_CRBG_Geoelectric**
    - **Isopach_Sub_CRBG_Geoelectric**
    - **Base_Sub_CRBG_Geoelectric**
    - **Top_CRBG_Geoelectric**
    - **Top_Sub_CRBG_Geoelectric**
  - *Columbia River Basalt Group Layer—Misc.*
    - **Isopach_Sub_CRBG**
      Isopach contours for the CRBG
    - **EdgeofCraton_Sub_CRBG**
      Digital representation of the edge of the Craton
    - **Isopach_CRBG**
      Digital representation of thickness of the Columbia River Basalt
  - **Isopach_Kittitas**
    Digital representation of contours showing thickness of the overburden in the Kittitas Basin
  - **Isopach_Pasco**
    Digital representation of contours showing thickness of the overburden in the Pasco Basin
  - *Puget Basin Layers*
    - **Puget_Sound_Quaternary**
      Polygons representing the thickness of the unconsolidated deposits or depth to bedrock.

        - **Isopach_Consolidated_Puget**
          Digital representation of isopachs of Ulatisian and Narizian surface-accumulated rocks
        - **Isopach_Ulatisian_Narizian**
          Isopach of Ulatisian and Narizian surface-accumulated rocks
        - **Isopach_Quaternary_Puget**
          Polygons representing the thickness of the unconsolidated deposits or depth to bedrock
    - **Isopach_Quincy**
      Digital representation of contours showing thickness of the overburden in the Quincy Basin
    - **Isopach_Selah**
      Digital representation of contours showing thickness of the overburden in the Selah Basin
    - **Basin_Base_Spokane**
      Digital representation of the elevation of the base of the unconsolidated sediments in the Spokane Basin
    - **Isopach_Toppenish_Satus**
      Digital representation of contours showing thickness of the overburden in the Toppenish-Satish Basin
    - **Basin_Base_Umatilla**
      Digital representation of altitude of top of Saddle Mountains Basalt, Umatilla Basin
    - **Isopach_Walla_Walla**
      Digital representation of contours showing thickness of the overburden in the Walla Walla Basin
    - *Willamette Basin Layers*
        - **Isopach_Aquifer_Willamette**
          Digital representation showing thickness of the Willamette aquifer
        - **Isopach_Silt_Willamette**
          Digital representation showing thickness of the Willamette Silt unit
        - **Basin_Base_Quaternary_Willamette**
          Digital representation showing altitude of the bottom of the basin-fill deposits in the Willamette Lowland
        - **Isopach_ConfiningUnit_Willamette**
          Digital representation showing thickness of the Willamette confining unit

        - **Top_Aquifer_Willamette**
          Digital representation showing altitude of the top of the Willamette aquifer
    - *Yakima Basin Layers*
        - **Isopach_Yakima**
          Digital representation of contours showing thickness of the overburden
        - **Basin_Base_Yakima**
          Digital representation of the elevation of the base of the unconsolidated sediments
        - **Alluvium_Base_Yakima**
          Digital representation of the thickness of the unconsolidated sediments
- *Oregon and Washington Well Layers*
  Digital representation of exploratory well locations adapted from many sources.
    - **Deschutes_gdwater_quality**
    - **Nehalem_Wells**
    - **Snake_Wells**
    - **Tyee_Umpqua_Wells1**
    - **Walla_Walla_Wells**
    - **Yakima_Wells**
    - **Chehalis_Wells**
    - **N_Will_wells**
    - **Puget_Sound_Wells**
    - **Sub_CRBG_Wells**
    - **U_Deschutes_Wells**
    - **Willamette_Groundwater_Wells**
    - **Coastal_Wells**
    - **Naches_Wells**
    - **S_Will_Wells**
    - **Tofino_Fuca_Wells**
    - **W_Olympic_Wells**
    - **Willapa_Hills_Wells**
    - **Klamath_Wells**
    - **Ochoco_Wells**
    - **Spokane_Wells**
    - **Tyee_Umpqua_Wells2**
    - **Whatcom_Wells**
    - **Astoria_Wells**
- *Oregon and Washington 1995 Oil and Gas Play Assessment Layers*
  The fundamental geologic unit used in the 1995 National Oil and Gas Assessment was the play, which is defined as a set of known or postulated oil and or gas accumulations sharing similar geologic, geographic, and temporal properties, such as source rock,

migration pathways, timing, trapping mechanism, and hydrocarbon type. Multiple layers are available:

- **pr402g**
- **pr452g**
- **pr401g**
- **pr450g**
- **pr1801g**
- **pr1803g**
- **pr1802g**
- **pr403g**
- **pr405g**
- **pr407g**
- **pr410g**
- **pr502g**
- **pr404g**
- **pr406g**
- **pr408g**
- **pr451g**
- **pr501g**
- **pr503g**

- *Pacific Outer Continental Shelf Region Oil and Gas Play Layers*
  - **POCSR_Growth_FaultPlay**
  - **POCSR_Neogene_ShelfSandstonePlay**
  - **POCSR_Neogene_FanSandstonePlay**
    Pacific Outer Continental Shelf Region (POCSR) Play outline was digitized to represent the area encompassed by the Neogene Shelf Sandstone (conceptual) Play.
  - **POCSR_Paleogene_SandstonePlay**
    Pacific Outer Continental Shelf Region (POCSR) Play outline was digitized to represent the area encompassed by the Growth Fault (conceptual) Play.
  - **POCSR_Melange_Play**
    Pacific Outer Continental Shelf Region (POCSR) Play outline was digitized to represent the area encompassed by the Melange Play.

- **US_GeologicUnits**
  This data set contains boundaries and tags for major geologic units in the WESTCARB states.

SOURCE LAYERS

Shapefiles available for viewing via the WESTCARB Interactive Map and/or download via the FTP site:

- **Cement_and_Lime_Plants**
  Point features representing cement and lime plants in WESTCARB states.
- **Gas_Processing_Plants**
  Point features representing oil and gas processing centers in WESTCARB states.
- **Power_Plants**
  Point feature class representing power plants in West Coast Regional Sequestration Partnership states.
- **Refineries**
  Point features representing refineries in WESTCARB states.
- **BC_Oil_and_Gas_Facilities**
  Oil and gas facility locations for British Columbia (data are from the British Columbia Oil and Gas Commission). Only available via the FTP site.

BASE LAYERS

- **WC_StatesDetailed**
  This data set portrays the State boundaries of the contiguous states that are members of the West Coast Regional Carbon Sequestration Partnership (WESTCARB). The original data set was created by extracting the State boundary polygons from the individual 1:2,000,000-scale State boundary Digital Line Graph (DLG) files produced by the U.S. Geological Survey. These files were then merged into a single coverage.
- **WC_StatesSimplified**
  Simplified representation of the boundaries of WESTCARB states.
- **AK_Geonames**
- The Geographic Names Information System (GNIS), developed by the U.S. Geological Survey in cooperation with the U.S. Board on Geographic Names (BGN), contains information about physical and cultural geographic features in the United States and associated areas.
- **AZ_Geonames**
  GNIS data containing information about physical and cultural geographic features in the United States and associated areas.

- **CA_Geonames**
  GNIS data containing information about physical and cultural geographic features in the United States and associated areas.
- **NV_Geonames**
  GNIS data containing information about physical and cultural geographic features in the United States and associated areas.
- **OR_Geonames**
  GNIS data containing information about physical and cultural geographic features in the United States and associated areas.
- **WA_Geonames**
  GNIS data containing information about physical and cultural geographic features in the United States and associated areas.
- **BC_Geonames**
  Toponymic information is based on the Geographic Names Data Base, containing official standard names approved by the United States Board on Geographic Names and maintained by the National Geospatial-Intelligence Agency.
- **AK_ArcticRefuge**
  The coverage depicts the official legislative boundary of Arctic National Wildlife Refuge.
- **US_Interstates**
  This data set portrays the Interstates in the United States.
- **US_StatesDetailed**
  U.S. state boundaries
- **WC_Railroads**
  This data set includes railroads in the WESTCARB states.
- **WC_MajorRoads**
  This data set portrays the major roads in the WESTCARB states.
- **WC_StreamsWaterBodies**
  The data set portrays the polygon and line water features of the WESTCARB states.
- **US_StatesGeneralized**
  U.S. state boundaries (Generalized)
- **WC_BuiltUpAreas**
  U.S. National Atlas Urbanized Areas represents urban areas in the WESTCARB states derived from the urban areas layer of the Digital Chart of the World (DCW).
- **WC_Cities**
  U.S. Cities represents locations for cities within the WESTCARB states with populations of 10,000 or greater, all state capitals, and the national capital.
- **BC_Province**
  Canada Provinces represents the Canadian provinces and territories as well as coastline, international boundaries, provincial boundaries, and demographics. The boundaries are digitized from CanMap®.
- **BC_StreamsWaterBodies**
  Drainage (coastlines, rivers, lakes) in British Columbia

Raster Files

- **Hillshade**
  Shading for cartographic purposes
- **Elevation**
  Global land 1-km base elevation